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BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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BERMUDA: A PARTIALLY DROWNED, LATE MATURE, PLEISTOCENE KARST

BY J HARLEN BRETZ

ABSTRACT

During Pleistocene time, the Bermuda Islands repeatedly underwent partial inundation and re-emergence. The land areas were continuously attacked and reduced by rain and ground water but repeatedly renewed, during times of submergence, by deposition of marine limestone and by contemporaneous additions of shore-born and wind-transported carbonate sand, now eolianite. Soils formed under subaerial conditions are now buried beneath later deposits and constitute important stratigraphic markers. The igneous foundation rock appears to have been exposed during some low marine stands, and the former shore lines seem to be recorded by submerged terraces. The major karst features are largely below sea level, and they must date from times of continental glaciations.

Previous writers have assigned eolian accumulation to times of Pleistocene low sea level and soil-making to times of interglacial high sea. Both conclusions are held to be erroneous.

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INTRODUCTION

The curvilinear fingers constituting the Bermuda Islands enclose or nearly enclose almost 60 square miles of sounds, reaches, harbors, and bays, approximately three times the total land area. Bermuda's land rock is nearly 100 per cent calcium carbonate and so permeable that the surface of every land-locked swamp and pond is at sea level, and the contained water is salt or brackish. There is no running water except in gutters and on concreted catchment areas, and almost no fresh ground water. Ten enterable caves have seawater pools (maximum depth 80 feet) whose levels vary with the tide. Large, apparently unaltered stalagmites and stalactites are completely submerged in the cavern-contained salt water.

Figure 1 suggests that reefs may enclose the larger tidewater-filled areas; however the geological evidence indicates (1) that Bermuda of today is only a skeleton of a once-continuous carbonate land area, (2) that evisceration on a remarkable scale by rain and circulating ground water has occurred, and (3) that during epochs of growth interrupting the solutional attack, the coastal margins of the island tract have been built up.

Most of Bermuda's above-tide rock is calcium carbonate eolian sand, sufficiently indurated to serve as building stone and to constitute the sea cliffs which dominate the shore lines. Rows of hills of this eolianite characterize all the

FIGURE 1.—OUTLINE MAP OF THE BERMUDA ISLANDS

large islands of the group and consistently parallel the coasts. Dune forms still survive among the younger hills, although somewhat reduced by rainwater solution. Calcium carbonate, carried down into the dune sand, has caused the induration.

Despite the widespread cementation, the indurated eolianite contains many pockety masses of friable, even loose, sand which have been protected from downward-infiltrating calcium carbonate by densified overlying material that appears originally to have been a surface crust, although now deeply buried.

Prompt cementation at the very surface of an accumulating body of eolian sand is further evidenced by palmetto-leaf impressions in lee-slope dune bedding. Also the lack of blow-out concavities is evidence that local anchoring by dune vegetation did not give rise to associated local erosional concavities on windward slopes and further supports the argument for prompt cementation of Bermuda dune sand.

The Bermuda dunes are coastal dunes which did not migrate from their feeding grounds, the shore lines. Therefore eolian accretion as recorded on the present islands occurred only at times of high sea level.

Solutional reduction occurred uninterruptedly as the land area increased from Pleistocene eustatic lowering of sea level and as the coastal regions thus were shifted into presently submerged areas. It was during such times of prominent emergence that the soils formed *terra rossa* regoliths which, because of later high sea level, were buried under eolian accumulations to constitute the conspicuous red paleosols. The paleosols thus largely record continental glaciation, whereas the eolianites record interglacial high sea levels.

The solutional caves of Bermuda, products of former ground water and now partially drowned in sea water, date from times of widespread emergence, as do the huge solutional depressions presently flooded to constitute most of the sounds, harbors, bays, and reaches of the little archipelago. Cavern collapse accompanying solutional reduction of these areas, plus marginal eolian upbuilding, explains the nearly or quite enclosed marine water bodies.

Differentiation of the stratigraphic elements of Bermuda has been based on paleosols, disconformities with basal conglomerates, mineral content, topography, and invertebrate fossils. No one criterion ranges through the

ISLANDS BY AND AIR FORCE MODIFICATIONS OF THE SHORE LINE

entire column, and that "column" is about as far from a conventional "layer cake" succession as are Pleistocene sections in the northern United States.

Sayles (1931) has made the outstanding contribution to Bermuda's geological history to date. Sayles' stratigraphy contained four eolianites separated from each other by three soils and from an underlying marine limestone by a fourth soil. Beneath this limestone was a fifth soil, then another marine limestone, and below that a fifth eolianite. Some of the names he used were redefined from earlier authors, most of them were new. The list is as follows:

Present soil
Southampton eolianite
McGall's soil (accretionary)
Somerset eolianite
Signal Hill soil (accretionary)
Warwick eolianite
St. George's soil (residual)
Pembroke eolianite
Harrington soil (accretionary)
Devonshire marine limestone
Shore Hills soil (residual)
Belmont marine limestone
Walsingham eolianite

H. A. Lowenstam and I, who worked together in the area, are unable to accept Sayles' formational ranking of the three uppermost eolianites separated by two accretionary soils. We accept only the Harrington as a record of an interval of soil-making under conditions of repeated, but minor, carbonate-sand contributions.[1]

Both physically and chemically, accretionary and residual soils are very different products of subaerial exposure. Accretionary soils in section are simply iron- and/or carbon-stained short linear portions of an eolian carbonate sand and commonly contain more land-snail shells than does contiguous unstained eolianite. They record limited vegetated tracts in protected places which received occasional additions of wind-blown sand. Residual soils[2] are deep-red

[1] Lowenstam has stated orally, without specific details, that in 1957 he found a marine member above Pembroke eolianite and beneath a St. George's soil in Spencer's Point cliff. This item will be commented on later.

[2] Because they contain small quantities of calcium carbonate blown in during soil development and also a small fraction of material not derived from limestone, they are not wholly a residuum of weathering. R. V. Ruhe prefers not to use the term "residual" for them.

to chocolate-brown clays and loams with no snail shells and little lime other than "rootlets" made by later infiltrations. They commonly rest on a surface of solution-made pinnacles and pockets (soil lapies) whose relief may be several feet.

The Bermuda Islands constitute less than 10 per cent of the carbonate-covered summit of a truncated volcanic cone whose rock has been reached in several drill holes. This calcareous platform is highest along its southeastern margin where it is rudely outlined by the islands. The northern margin of the elliptical platform has but one tiny land mass, North Rock (Fig. 2).

Today, the submerged platform is a great shoal or lagoon nowhere more than 60 feet deep and averaging much less. During glacial times, it undoubtedly became emergent, just as undoubtedly the marine limestones, now as high as 100 feet A. T., record interglacial epochs.[3] Sayles saw the greater Bermuda of periods of glacial low water as a desert with traveling dunes, some of which reached and climbed up on the southeastern rim to make the eolianites. He thought that ensuing rise of sea level brought such deposition to an end and that interglacial times were marked by soil-making and erosion only.

The concept developed by Lowenstam and the writer, checked and accepted by Ruhe, completely reverses Sayles' sequence. The most conspicuous evidence for this reversal, *i.e.*, for eolianite deposition during high sea levels, is in the dune forms still surviving from the latest, although not the greatest, marine high of the past.

Acknowledgments

This paper covers chiefly the geomorphic part of an investigation of Bermuda's geological history undertaken in 1956 by H. A. Lowenstam and the writer. Office study of field data in early 1957 revealed a need for further work on stratigraphy, and Lowenstam spent part of that summer on such problems. R. V. Ruhe was persuaded to give a few weeks in 1957 to a study of Bermuda's pedologic problems which Lowenstam and Bretz were not competent to handle. Funds for Lowenstam's work were provided by the California Institute of Technology; Bretz had a National Science Foundation grant; Ruhe had a grant from the Penrose Bequest of The Geological Society of America. Ruhe's pedologic study of Bermuda's paleosols was done in collaboration with his colleagues J. G. Cady and R. S. Gomez of the Soil Survey Laboratory, Soil Conservation Service. Ruhe's manuscript is being prepared for publication. Lowenstam's contributions on stratigraphy, paleontology, and submarine topography should see publication before long.

Dunes and Eolianites

Sayles' happy invention of the term "eolianite" enables us to describe all wind-transported and wind-deposited material on Bermuda with one word, whether or not the material originally had dune form and structure. Steep, parallel, lee-slope bedding characterizes any considerably modified eolianite deposit as a former dune. Much Bermuda sand rock was perhaps never heaped in drifts with the characteristic dune profile but may have been accumulated in relatively thin sheets of superimposed minor drifts. Sections of such tracts would probably show cross-bedding exceedingly variable in direction and degree of dip and in thicknesses of successive units, and that most characteristic feature of wind-deposited sand: repeated minor truncation of once-continuous laminae, with deposition across the truncated edges by later beds with widely variant dips.

Dune-shaped hills on Bermuda are limited almost entirely to coastal tracts but are not uniformly distributed. The north shore of the main island, facing the lagoon and extending 3½ miles west from approximately the entrance to Harrington Sound almost to Spanish Point, has no dunes but is continuously cliffed with few indentations, projections, or small off-lying islands. For the entire distance, the cliffs are in Devonshire indurated beach rock which may be seen to overlie eolianite at Barker Hill and Black Watch Pass road cuts.

Well-formed dunes are also lacking along the lagoon shore of the northern coast line between the entrances to Harrington Sound and Ferry Reach. Here, however, the cliffs are cut in a complexly bedded eolianite that extends to the northern tip of St. George's Island and,

[3] Two bore holes are reported to have shown eolianite at 100 feet and 245 feet below tide. If correctly identified, such eolianite, although very probably pre-Walsingham in age, can hardly be pre-Pleistocene. These depths much exceed those of the lagoon floor, which therefore appears to have been notably aggraded during Pleistocene submergences while the islands have been built up locally more than 400 feet. The original bore hole was started at 135 feet A.T. and penetrated 380 feet of sedimentary rock, proving that Bermuda's higher hills are not perched on high volcanic rock.

in St. George's Parish, is the foundation rock on which stands, on Ferry Peninsula and St. George's Island, a long row of simple, well-marked dunes.

Lake, and Spital Pond have been enclosed in large part by such dunes. Farther west and southwest successive coalesced rows of dunes cover nearly the entire width of the island.

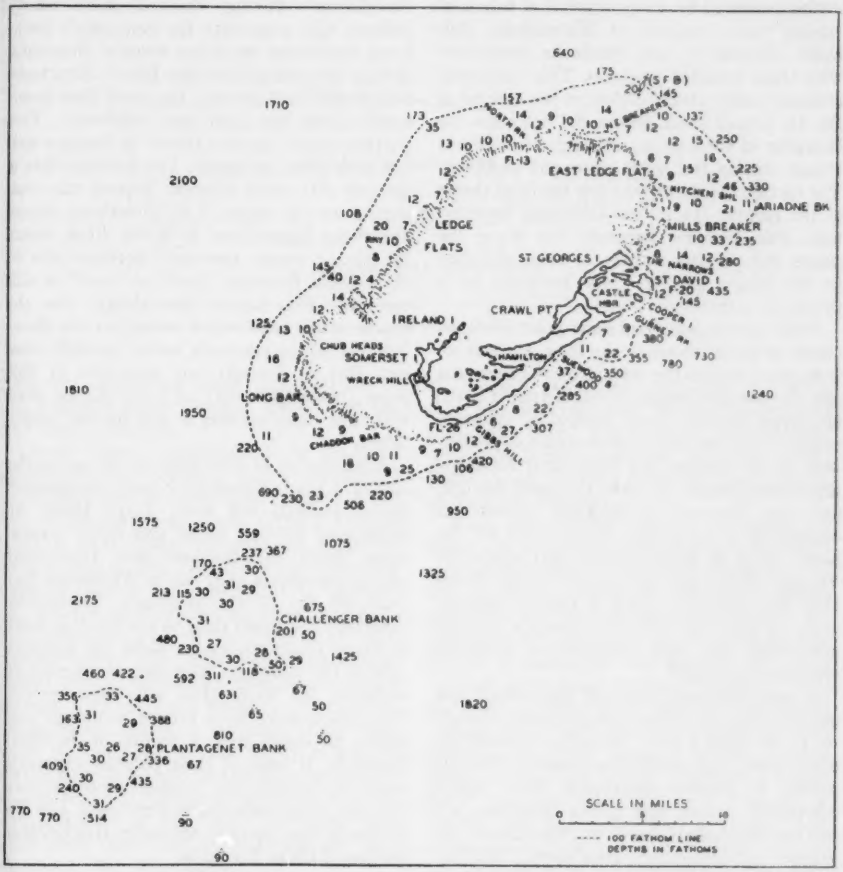

FIGURE 2.—BERMUDA ISLANDS WITH THE ADJACENT BANKS
From Sayles (1931)

This northern shore facing the lagoon contrasts strikingly with the southern coast. Although cliffs have been cut there in the older rock of Bermuda, dunes are piled high above and back of those cliffs. Along other stretches, dune forms are readily identified at shore level and are themselves being cliffed. Islands partially shutting Castle Harbor off from the Atlantic to the south are remnants of younger Bermuda dunes. Trott's Pond, Mangrove Gibbs Hill lighthouse is a marker for the higher part of this dune complex.

This contrast between northern and southern sides of the island group indicates that the shore line of the lagoon to the north contributed much less eolian sand during Bermuda's later dune-building history than did that of the open sea to the south. It seems to indicate a marked contrast in dune-building winds rather than in quantity of sand available.

Sayles (1931, p. 445–446) grasped a fundamental feature of Bermuda's geomorphology when he indicated that two Bermudas are recorded in the existing islands, an Older and a Younger. The Older Bermuda was an "original nucleus, reduced by a long interval of subaerial erosion" and consisted of Walsingham, Belmont, Devonshire, and Pembroke formations with three included paleosols. This "subaerial erosion" culminated therefore in the making of the St. George's soil. Sayles did not state the character of the erosion, although he ruled out stream erosion and noted caves and sinkholes. The specific character, which is the chief theme of the present study, was solutional degradation. The Younger Bermuda lies along the coasts and consists entirely of dune additions to the "much smaller Older Bermuda by a process of accretion."

From almost any good view point of ocean coasts or inland shores or sky lines, one can see some parts of both the older, erosional Bermuda and the younger constructional Bermuda in the landscape. Sayles' "long interval of subaerial erosion" was the end of *terra rossa* soil production on the islands. His three later eolianite-depositing episodes are here telescoped into one, and the "interval of subaerial erosion" is considered to have been longer than all the later period of dune-building that made the Younger Bermuda. Because the earlier Shore Hills soil records as long a time of wasting away as does the later St. George's soil, we hold that two long intervals of subaerial erosion are recorded.

A dune form may undergo degradation and modification, yet retain enough original character to be called a dune. Virtually all Bermuda dunes have been modified somewhat. Not one retains its original magnitude. Rain, which commonly washes and gullies hillslopes, has reduced Bermuda's dunes by solution on the exposed surfaces during their growth and has carried its take down into the permeable sand, cementing the dunes almost everywhere to the grade of a usable building stone for ordinary structures. Quarries obtain satisfactory building stone even on the very summits of some of the youngest dunes, and the outcropping edges of inclined beds on gentler slopes suggest the pattern of outcrop found in folded rocks.

Contrast in degree of induration between rocks of the Older and Younger Bermudas is almost as marked as are the land forms. But among the dunes themselves, there is almost no difference in extent of consolidation, suggesting that they all date from one epoch of dune-building.

The least crowded and therefore most readily recognized group of dunes is probably that on the peninsula north of Ferry Reach, St. George's Parish, where a dozen nearly isolated hills constitute the peninsula's backbone. Southward lee slopes descend diagonally toward and almost into the Reach. Structures and profiles indicate that the wind blew dominantly from the west and northwest. This northern coast line has almost no beaches and has cliffs along its length. The 5-fathom line is scarcely 200 yards offshore. Beyond this line, depths do not exceed 8 or 10 fathoms across the entire lagoon floor to North Rock where the almost wholly destroyed northern rim of the original Bermuda "reef" or "atoll" is still recorded. This lagoon floor clearly was the source of the sand which went into the dune-building on the peninsula before the cliffs were cut. But as brought out elsewhere in this paper, contemporaneity of a dry lagoon floor with this dune-building is not thereby established.[4]

A foundation of older rock for the peninsular row of dunes is recorded by good exposures of buried residual soil along Ferry Road, an abandoned railroad grade, and other excavations. Both the Belmont and Devonshire marine limestones crop out in Whalebone Bay near the tip of the peninsula. Devonshire limestone is exposed close to the low-tide mark in Ferry Reach depression along the southern side of the peninsula, and Belmont limestone underlies the Shore Hills soils type section. Thus there must have been a peninsula here before the dunes grew, a portion of the Older Bermuda. If some of these paleosol exposures are of St. George's soil, as seems probable, then the underlying eolianite is Pembroke, and the peninsula thus contains the entire stratigraphic section of Older Bermuda.

At the north end of Whalebone Bay, a youthful soil which certainly is not the mature St. George's overlies the Devonshire marine limestone. It contains both marine and land shells, the percentage of marine forms increasing westward down-slope toward the sea (Fig. 3). The soil here appears to be partly beach sand and partly eolian sand, somewhat mixed by

[4] A few small, fragile pelecypod valves have been found in cuts well up in the Ferry Peninsula dunes. Even if derived intact from marine rock on a desert floor, they could hardly have survived the working-over required by the migration Sayles envisaged.

waves and wind of its time. It probably is the Harrington accretionary soil, and the overlying eolianite therefore is Pembroke.

The important point here is that eolian sand was deposited just up-slope from a beach. Sea level was therefore high, and the lagoon floor was submerged when accumulation of this eolianite began. Sayles' theory will not take care of this fact.

Verrill (1902) estimated from insoluble substances in the eolianites that a residual soil 1 foot thick required solutional removal of 200 feet of once-overlying sand. Although Sayles (1931, p. 443) halved this estimate, the implications are startling. To form Sayles' estimated 2 feet of average thickness of the St. George's soil, 200 feet of Pembroke eolianite must have been removed. Even if we discount for presumable wash into depressions that made thicker patches which may have been taken as average and for sand blown in during soil development, Sayles is indicating that Pembroke Bermuda was approximately as high as are the later dunes and that all this was reduced by rain to the St. George's soil residue and any surviving hills of the Older Bermuda. How much have these later dunes themselves been reduced by the same process?

Soils on the dunes are not *terra rossa* soils but do have soil-base densifications which on deforested and rain-washed slopes show a kind of armor (with plenty of chinks). Sayles' estimate of average thicknesses of 6 inches for the modern soils requires a reduction of 50 feet of the dunes since growth ceased. Most of his assumed 50 feet of calcium carbonate removed by solution presumably has been added interstitially to the original piles of loose sand to make the consolidated rock of today. The dunes have become "petrified" where they stood and still stand.

Consolidation began as soon as the dunes began to grow. The plant carbon in the accretionary soils indicates that Bermuda had rains during eolian dominance, as do root casts, land snails in some portions of the dune eolianites, and the surprising preservation of molds of partially collapsed palm-like leaves in otherwise clean eolianite. The last case indicates that both burial and incipient consolidation must have been very prompt. Grape Bay cliffs, Paget Parish, have the most convincing display of these leaf impressions.

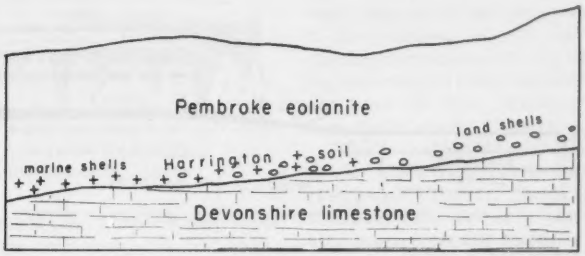

FIGURE 3.—DIAGRAM OF SECTION AT WHALEBONE BAY, BERMUDA ISLANDS

Along the southern coast of Bermuda, the dunes are so crowded and massive that most view points offer no individual silhouettes like the spaced-out dunes of the Ferry Reach peninsula. Yet the sea cliffs south of them, the old lowlands of the islands in Great and Little Sounds to the north, and the *terra rossa* soils exposed at intervals between all testify to a platform of older rocks beneath the dunes, comparable to the situation on the northern peninsula. In a few stretches of the southern coast, the platform for the later dunes apparently is a little below sea level. The row of islands and peninsulas that partially close Castle Harbor off along its southern margin are badly battered survivors of a former probably complete row of younger dunes.

An outstanding feature of the southern coastal dunes west of Castle Harbor is the enclosed salt or brackish ponds, lakes, and marshes (*e.g.* Trott's, Mangrove, Spital, Paget) and the low elongated valleys lying parallel to the coast line. They seem clearly to be linear tracts between rows of dunes, relics of the old Bermuda topography that escaped obliteration during the last epoch of eolianite aggradation. In some places in Paget and Warwick parishes, four rows of dunes appear to be identifiable, although varying dune

lengths make them very irregular. The dunes of the northern row may have traveled completely across the lowlands, followed by another wave of dunes and that by another until almost the entire width of the island here, nearly half a mile, became rebuilt with hills that today reach 100 to 200 feet and more A.T.[5]

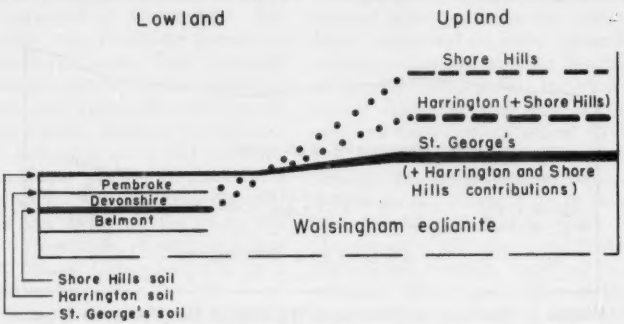

FIGURE 4.—DIAGRAM TO SHOW CONTRAST IN SOIL RECORD ON UPLANDS AND LOWLANDS, BERMUDA ISLANDS

This concept, however, is less appealing to us than the picture of each row having grown where it now stands, the south side of the island thus having been built up and out by addition of successively younger rows. Sayles thought the area of Older Bermuda became considerably increased by these additions, to make the Younger Bermuda. But Older Bermuda formations and soils must underlie the later dune belts, for they crop out in many places along this southern coast line.

These linear elevations and their intervening depressions are well shown by the 20-foot contours of the Hamilton, Bermuda sheet 8048 111 SW, Series E 812, Army Map Service, Corps of Engineers, U. S. Army, 8-1955.

PALEOSOLS

If no soils had been made, or preserved, on Bermuda, its stratigraphy today would consist of the two marine limestones and only two or perhaps three eolianites. Even by using buried soils as markers, the present study combines Sayles' three youngest eolianites (Warwick, Somerset, and Southampton) into one formation, the sand constituting the dunes of the Younger Bermuda. It rejects his two youngest soils (Signal Hill and McGall's) as trustworthy stratigraphic markers. Neither of these soils is more than a brownish coloration of limited lateral extent in the eolianite itself. Neither is a residual accumulation of materials less soluble than calcium carbonate. Sayles recognized this contrast when he described them as "accretionary".

Undoubtedly neither of the two marine trangressions completely submerged the Bermuda then consisting of Walsingham eolianite, and so a soil continued to form on such continuously emergent land surfaces from the close of Walsingham aggradation up through the times of both marine overlaps, of the erosional interval separating them, and of all later time until, if ever, it was destroyed or buried (Fig. 4). The oldest known paleosol (Shore Hills) can be identified with confidence only where developed on Belmont marine limestone and buried under Devonshire limestone. Above the level reached by the Devonshire sea (100 feet A.T. maximum known) and in areas not covered by the Pembroke eolianite, a residual soil under post-Pembroke sand might represent all time from the close of Walsingham aggradation to the beginning of Sayles' Warwick accumulation. The soil on a Walsingham upland, developing cumulatively through all of Older Bermuda's history, necessarily migrated downward while the adjacent lowlands were being built up and their soils locked into a stratigraphic sequence.

This picture requires acceptance of the idea that, whatever the climate, soils were continu-

[5] When emerged, the narrow shelf offshore from these dunes provided far less sand for growth of desert dunes than did the emerged lagoon floor. Yet the highest, most massive, and most crowded dunes are here instead of along the lagoon shore.

ously formed in unsubmerged places favored by topography and a lack of concomitant deposition.

Lowenstam and the writer saw the type localities of all of Sayles' soils and are convinced that only the Shore Hills and St. George's

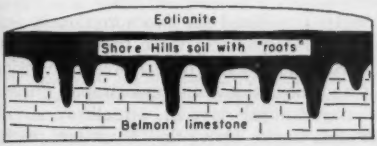

FIGURE 5.—DIAGRAM OF SHORE HILLS TYPE SECTION, BERMUDA ISLANDS

deserve the name of soils. These are deep red or chocolate brown *terra rossa*, 1–4 feet thick; they overlie irregular surfaces of solution pits and pinnacles (soil lapies), and they commonly have a "soil base" (Sayles, 1931, p. 430) of very dense, almost porcelaneous rock which is commonly banded as in a concretionary growth. This base may be 1–2 inches thick on unaltered underlying rock.[6]

A striking feature of the contact are the soil "roots" (Fig. 5), sharply defined vertical cylindroids or elongated cones of red clay which penetrate as far as 8 feet below the average soil bottom and are outlined commonly by casings so firmly cemented that wave erosion may leave them standing as much as 2 feet in relief. Sections, both vertical and horizontal, may still possess a red, clayey central filling indurated by a later calcification. The casings apparently are downward extensions of the soil base. Where numerous and close together, they seem to indicate former basinlike tracts with a maximum catch of water for downward percolation. They are locally termed palmetto trunks and may, indeed, have been initiated by large plants with "tap-root" character during early stages of the soil's formation.

Sayles' term for all the other soils (accretionary) refers to eolian sand that accumulated so slowly that, under concomitant weathering, it became yellowish to reddish. In places, these "accretionary" soils have only a faint tan color or are slightly brownish from included plant carbon. They are all highly calcareous and contain land-snail shells. They have almost no clay. They grade both downward and laterally into clean eolianite. Their thicknesses are exceedingly variable, but where thickest the contained clay and residual insoluble materials, if undiluted by the calcareous-sand constituent, would make a very thin layer indeed. If they are to be considered as soils, they are very immature, even embryonic, products of weathering and, except perhaps for the Harrington, do not have the time significance Sayles read from them; namely Pleistocene ages.

The St. George's residual soil is very similar to the Shore Hills but overlies an eolianite (Pembroke). The St. George's soil and the Pembroke eolianite can be identified positively only where a marine limestone lies below the eolianite. Without that, the soil could as logically be considered as Shore Hills developed on Walsingham eolianite protruding above the level of the Belmont sea. This difficulty springs from the lack of trustworthy physical or chemical criteria for specifically identifying any soil or eolianite. Sections showing marine limestone beneath an eolianite with a red, clayey soil do exist, although they are rare. In many places Sayles cited as definitely showing one or the other of these two soils, the red paleosol may be either Shore Hills or St. George's.

The one accretionary soil to which Lowenstam and the writer give stratigraphic value is the Harrington, which by Sayles' definition overlies the Devonshire marine limestone and underlies Pembroke eolianite. Being a record of eolian deposition as well as of weathering, it probably represents a slow beginning of Pembroke accumulation. But it also records the initial withdrawal of the Devonshire sea, inasmuch as in several sections its seaward basal part contains marine fossils as abundant as the land snails in its upper landward part. When deposition of the Pembroke eolianite of Whalebone Bay began, sea level was as high as it is today.

By the concept of soil distribution herein advanced, the Harrington soil was formed not only on the Devonshire but must have been formed also above the Devonshire upper limits and there would overlie (or be a part of) Shore Hills soil. The Harrington soil is generally identifiable from its internal characteristics without reference to the underlying Devonshire marine rock. Except in one place, the stained zone is markedly thicker and the yellow-brown

[6] Unpublished studies by R. V. Ruhe, J. G. Cady, and R. S. Gomez show that both Shore Hills and St. George's soils are polygenetic. They record superimposed weathering cycles caused by interrupting episodes of carbonate sand addition. This sand they call "primary" carbonate as distinguished from lime carbonate infiltrated after burial under a post-soil deposit. They found no "original" carbonate.

color much stronger than in any of Sayles' younger soils. The Harrington possesses no soil roots or soil base even where thickest and most deeply colored. The only sections where the color might be misleading are those showing truncation of Shore Hills soil by Harrington soil. Down-slope from such transections, the Harrington may be as red as the older soil because of incorporation of material from erosion of the subjacent Shore Hills. A very limited exposure thus might be misinterpreted, because not all Shore Hills sections show "roots" or a soil base.

In Sayles' "most important section in Bermuda", along the Paget-Warwick parish line, he identified a *terra rossa* soil near the north end of the section as Harrington. The exposure is close to sea level, too low to show its bottom part, so the existence or lack of soil roots and soil base remain undemonstrated. But it is no slightly reddened zone in eolianite otherwise essentially unaltered, as is his type Harrington section, and as his description calls for. It is either St. George's or Shore Hills, and its low altitude indicates the latter. The problems of identification at this place are directly consequent on the lack of specific identifying characteristics for any one soil of either of the two groups, residual and accretionary. Only order of superposition can be used to differentiate Shore Hills soil from St. George's soil unless there is a marine limestone in the section. Because the paleosols are rarely so exposed that one can be sure of such an order and because all soils had an original undulatory profile, this criterion of superposition is seldom usable.

The St. George's soil, overlying the Pembroke eolianite, should lie at higher altitudes than the Shore Hills. But it is very probable that higher occurrences of Shore Hills were not inundated by the Devonshire transgression, and some did not receive a Pembroke cover. Thus, as previously noted, the soil development in such places would span all of Shore Hills, Devonshire, Harrington, Pembroke, and St. George's time. Varying thickness of any given soil in different places, because of a variety of factors, makes thickness unusable for identification.

Because St. George's soil overlies Pembroke eolianite, and portions of Shore Hills soil above the Belmont level must lie on Walsingham eolianite, and also because only order of superposition can differentiate the two eolian formations, the character of the subjacent formation is not diagnostic for a residual soil unless the substrate is a marine limestone.

Sayles (1931, p. 430) found an extinct land snail, *Poecilozonites nelsoni*, no higher stratigraphically than the Harrington soil. Lowenstam confirms this. But since both Harrington and St. George's soils not uncommonly are seen in stratigraphic succession and are markedly unlike physically, this criterion is only confirmatory.

Sayles considered the two accretionary soils as markers separating three upper eolianites. He believed their distribution was island-wide, but we believe this is undemonstrable. There is no conventional layered structure on the Bermuda islands above the Devonshire marine limestone. The deposits constituting the existing dunes were patchy at any time, and locations of patch growth became altered repeatedly as accumulation occurred. There is no way of determining, at present, whether one particular reddish or brownish zone in these dune deposits antedates or postdates another such zone unless superposition is evident. During the accumulation of the later Bermuda dune sands, local pauses in accretion resulted in local ferric reddening and local carbonaceous browning in such tracts as were more slowly aggraded for a few centuries. Such scattered showings cannot be correlated reliably. The section which Sayles said (1931, p. 397) exposed "four of the five soils . . . in such relations as to preclude any possible doubt that each soil represents a distinct and separate horizon" was examined by Lowenstam and the writer and later by R. V. Ruhe, all of whom concluded that Sayles correctly identified the lower two soils as Harrington and St. George's but that his Signal Hill and McGall's soils are only stained local places, and are not of stratigraphic character for the islands.

For the sake of a specific record of this departure from Sayles' picture of Bermuda history, the following description from the writer's field notes is here given. Ruhe reached a comparable re-interpretation.

"We found 'roots' of Shore Hills soil close to tide level in Mullet Bay's low cliffs. These are not noted by Sayles. Had he found them, he would have claimed that all five of his soils were present. Erosion (by Devonshire waves) has destroyed the soil itself and the internal cavities of the 'roots'; plus the spaces separating them have been filled with Devonshire marine sand. A Harrington soil profile (such as it is) was then made in the upper Devonshire sand and continued in the first eolian accretions as the Pembroke epoch began. This stained sand definitely is not a residual soil and cannot be a record of a glacial or an interglacial interval.

"Farther east along the road in the first of the sections described by Sayles, his identification of

the Harrington soil is accepted. Sayles reported no fossils from it. We found Devonshire marine fossils in its lower part and pulmonate snail shells in the upper reddened zone. It is definitely an eolianite deposit throughout [and defintely made along a shore line].

"An unstained eolianite overlies this Harrington zone and is accepted as Pembroke. Over the eolianite is a true clayey residual soil, Sayles' type St. George's with 'roots' like those of the Shore Hills record. Because it clearly lies higher stratigraphically than the Shore Hills roots, it is a later soil.

"With several breaks, we traced this St. George's soil according to Sayles' description almost to the Khyber Pass Road where it disappeared under an eolianite, his Warwick. This proved to have consistently southward-dipping stratification all the way up Signal Hill to the north, to the summit of the road, 120 feet A.T.

"At the summit a shallowly buried, slightly reddish or brownish member shows in the road cut. It is poorly indurated and stratified and apparently lies on a surface of erosion but possesses no soil roots or base. This is the type exposure of Sayles' Signal Hill soil. It records some break in growth of the big (180 foot A.T.) Signal Hill dune, and is evident that the dune is compound and that some change in winds occurred in a relatively brief interval of decreased rate of deposition. But it is not a soil.

"A low sag several hundred feet wide separates this exposure from one in the next hill northeastward. Here a pit provided exposure of Sayles' next younger soil, the McGall's. It is only a slightly reddish or brownish zone, with no soil roots or base. The profile across the pit wall is that of a shallow basin. The stained zone is thickest and most strongly colored in the low middle and diminishes toward either extremity to become finally unrecognizable. Since no order of superposition exists, this McGall's soil could be judged as earlier or later than, or contemporaneous with, the Signal Hill type exposure, at the whim of the observer.

"This buried local-basin profile, with intensification of color in the bottom and gradation up-slope into unstained eolianite, has been seen duplicated in numerous road, railroad, and sea-cliff sections. It means to us only a pause or slowing down in local accretion of dune sand from purely local causes (baffles or barriers of vegetation, foredune growth, *etc.*). It is not amenable to general application, not significant of climatic change and not correlatable with other concave patches of comparably stained units, either in time or in place. Acceptance of our interpretation debars acceptance of Sayles' Warwick, Somerset, and Southampton eolianites as successive formations and of his correlations of them with continental glacial and interglacial ages".

R. V. Ruhe reports (Personal communication) on a section at McGall's Bay which the writer did not see. Following Sayles, he identifies the Shore Hills, Harrington, and St. George's paleosols and, in eolianite above, two accretionary paleosols as strongly developed as, and even thicker than, the Harrington beneath. Although not in one vertical section, there is no question that there were five different times of exposure sufficiently long to leave records. Ruhe writes that "It is conceivable that extremely detailed work may prove the . . . (uppermost) two to be trustworthy stratigraphic markers. It is agreed, however, that with information now at hand they are questionable as trustworthy stratigraphic markers". But "the Signal Hill and McGall's soils must be recognized as soils *per se*. . . .

Sayles listed 10 definite exposures of Harrington and 10 probable ones. To that, we would add several more. For Signal Hill and McGall's soils, he listed five and four occurrences. In only two of these were the soils in a vertical sequence.

Because the Harrington soil of the Older Bermuda is preserved in patches, reconstruction of the local topography contemporaneous with any such remnant is questionable. We feel sure only about the littoral location of the Whalebone Bay exposures of Harrington. Development of the Harrington soil doubtless varied with slope and exposure to eolian increments. Locally, it may have advanced no farther than did Sayles' Signal Hill and McGall's soils in his Signal Hill sections. For the same reasons, soil pockets with greater accentuation than the two on Signal Hill may well have been formed in more favored situations.

We hold that the widespread occurrence of an accretionary soil between Devonshire marine limestone and its overlying Pembroke eolianite establishes it as a part of Bermudian stratigraphy, even if, as at McGall's Bay, it is less prominently developed than the two "soils" higher in the same section.

There are two highly stained soil zones in the cut on the north side of the road triangle 1500 feet directly north of the Bermuda Biological Station, St. George's Parish (Fig. 6). The lower one is horizontal in the plane of the section; the upper one slopes down to intersect or join the lower just at road level. Eolianite deposits underlie, separate, and cover the two zones. Neither soil shows "roots", and only the lower one has a good soil base, but both are much better developed soils than the type Harrington and far more so than Sayles' Signal Hill or McGall's soils. If they are interpreted as Shore Hills and St. George's soils, weakly developed because they were made on well-drained slopes, the subjacent eolianite must be Walsingham and the intermediate one Pembroke. The altitude is as low as the highest Belmont limestone known and well below the highest Devonshire; thus both formations must have once been present. The Belmont was removed in the making of the lower soil. That soil must

then have been burried under Devonshire. The marine limestone must then have been removed down to the soil; the soil zone itself was spared. After this came burial under Pembroke; then came the period of St. George's soil-making, and finally the burial of that soil.

Sayles hypothesized an equally strange stratigraphic interpretation at the type locality of the Shore Hills soil in a quarry scarcely a thousand feet distant. He identified the marine limestone beneath that very well-developed soil as Belmont, and we find no good reason to question it. If the identification is correct, there is no Devonshire limestone in the section, and the overlying eolianite logically is Pembroke or later. But how can a Devonshire cover be removed so as to exhume and yet leave intact, both here and at the road triangle an older subjacent soil?

The answer may lie in the method of erosion. Only two methods are applicable on Bermuda: wave and wind erosion, and rain and groundwater solution. Wave and wind attack apparently can be ruled out here because of the topographic situation. If only solutional attack occurred, any covering Devonshire might eventually have been removed down to the buried insoluble soil and that, instead of wasting away by solution as did the limestone, would have received additional insoluble substances derived from the Devonshire. The supposed Pembroke itself is only a small hill at the Shore Hills type locality and has no old soil on it. If this lack of a soil is taken to indicate post-Pembroke age of the eolianite, logic requires prior solutional removal of both Devonshire and Pembroke and demands the conclusion that this type section soil is actually a composite Shore Hills and St. George's soil.

Our preferred interpretation, however, is that the eolianite is not Pembroke but is an early Devonshire dune sand deposited in advance of the rising sea level. It protected the soil from wave erosion when the sea finally transgressed the site but became reduced subsequently (perhaps with overlying Devonshire marine and Pembroke eolian rock) to this small remnant on which no St. George's soil remains or perhaps ever developed. A thick red soil in a depression to the southeast, between the quarry and the Biological Station, thus would be composed of St. George's and all later soil, and might even have a Shore Hills component.

FIGURE 6.—DIAGRAM OF SECTION NORTH OF BIOLOGICAL STATION, BERMUDA ISLANDS

Difficulties comparable to those encountered in the road triangle section, the Shore Hill type section, and the Paget-Warwick section have been found in many exposures. They point up the contention that no Bermudian soil can be used alone as a stratigraphic horizon.

Attack on a buried soil by shore agencies leaves a different record. Wave erosion of Belmont rock during Devonshire transgression is clearly recorded in several places and will be discussed in more detail by Lowenstam. In some of these sections, there is no trace of an intervening Shore Hills soil beneath a Devonshire basal conglomerate. In others, perhaps near by, truncated soil roots in the Belmont indicate that the Shore Hills soil once was present. Elsewhere, chunks of a red clay have been found in the basal conglomerate of the Devonshire. Most striking are those exposures of truncated soil roots which, because of the firm cementation of their casings, stood in relief on the Devonshire beach and became both filled with and embedded in its sand. But no intact Shore Hills soil layer beneath Devonshire beach sand has yet been found.

A further comment on identification of Bermuda soils deals with deep red accumulations possessing subjacent solutional pits (soil lapies) with a pronounced relief but no cover of eolianite and no calcification later introduced into the soil profile. One of these is almost directly across the road from the two soils shown at the triangle intersection north of the Biological Station (Fig 6). It is a deep red, thick clayey soil with deep solution pockets disappearing below road grade in the subjacent rock. It has no cover rock, no tangle of infiltrated calcareous "rootlets", and no induration from a general diffusion of carbonate such as characterizes both Shore Hills and St. George's roots where comparably developed. Our preferred interpretation for this soil is that it represents both of the soil-making episodes recorded on the north side of the road and also the eolianite-depositing interval between and also all subsequent soil-making time; that no eolian sand has ever been blown over the site in quantity sufficient to survive as such during all post-Shore Hills time. Recalcification of a residual soil can occur only from a later burial. Any eolianite cover must be thought of as patchy, not continuous. Without burial or erosional removal, any Bermudian soil will go on developing during all succeeding epochs.

Caves

The numerous caves of Bermuda have long since ceased to enlarge, and most of them are only isolated portions of former extensive, integrated cavern systems. The surviving chambers have been isolated by collapse of roof rock and deposition of secondary dripstone. Thus closely adjacent caves with no traversable underground connections may be only segments of one original cavern. Also many former caves are now recorded only by solution-pocked, dripstone-draped sea cliffs.

If percolating rainwater descending into the caves is now contributing to their destruction by depositing the massive dripstone they contain, solution of the Bermudian caves must have occurred under different conditions. One conceivable condition would be greater rainfall. This suggestion would have validity only if the cave patterns, proportions, and orientations recorded as origin by descending water. As will be shown, they do not do this. Surviving solutional chambers are horizontally elongated, not vertically or steeply oriented. The circulation which made these caves moved in a nearly horizontal plane. A former body of fresh ground water, supplied and maintained by rain, is indicated. But the free entrance today of sea water beneath all the land denies the possibility of such a ground-water body forming in the present islands through increased rainfall alone. The rock must have been far less permeable, or the island must have been far larger to accumulate and retain a fresh ground-water body. The eolianite and marine limestones are progressively denser and less permeable with increasing age, and the solution caves are all in these older rocks. But even these rocks do not retain a ground-water body.

Arguments that Bermuda formerly was much more extensive, based on other grounds than the surviving caves, are discussed elsewhere in this paper. Earlier students have theorized that the now shallowly submerged Bermuda lagoon, approximately 250 square miles in area, exceeding 10 times the present land area, was emergent at one time.

It is readily conceivable that, coincident with such a great enlargement, an early Bermuda could have held a ground-water body derived from rain whose upper surface, the water table, stood well above that lowered sea level, even above the level reached by the sea today, high enough to saturate the lower part of the carbonate rock then standing on the emerged platform, the part containing the caves. As in all oceanic islands with fresh ground water, the water table would be a low dome under the central higher part of that land, and the ground-water body would extend downward, according to the Ghyben-Herzberg theory, about 42 times as far as the water table stood above sea level. The caves would be dissolved out where favoring conditions allowed seaward escape of the ground water from this dome. Only by this concept can many features of Bermuda caves find rational explanation.

A corollary to this thesis of cave origin is likely to be challenged because of its almost unprecedented demand for solution, chiefly by ground water, where ground water no longer exists. This corollary is that all the salt-water-filled, nearly land-locked depressions of Bermuda's submarine topography in carbonate rock have lost the rock that once constituted land, lost it largely because of cave-making and cave failure. Three-fourths of the island's area contained within its present coastal outlines has vanished. Three-fourths has gone back to the sea which gave it. The resulting relief, caused by solution alone, amounts to at least 300 feet, of which 70 feet is now submerged by the present world-wide oceanic high level.

Conviction that this is a correct conclusion may require the details which follow.

I have previously defended and elaborated the theory that most limestone caves have had their inception and largely their completion in continuously saturated rock below the water table of their region and that they exist as air-filled cavities today because of a subsequent lowering of that water table by deepening of nearby river valleys consequent on uplift of the cave region. Paradoxically a decrease in altitude above tide brought Bermuda's caves from a zone of saturation to a zone of aeration (plus salt-water pools).

Not all the criteria supporting this theory of phreatic origin have ever been found in any one cave, but genetic relationships once established can be safely extrapolated where gaps in a complete series exist. For Bermuda's caves, the evidences for sub-water-table origin are (1) near-horizontality of solutional chambers, (2) blind solution pockets in walls and ceiling, requiring a tube-full circulation, (3) restriction of all solution caves to lower stratigraphic members, (4) the obvious former continuity at those low levels of now-isolated cave units, and (5) the lack of evidence for solutional enlargement of passageways by water descending toward the cave-inhabited low levels or by free-surface cave-floor streams.

Topographies dominantly of solutional origin, usually classed as karst, involve sinkholes either from roof collapse of subjacent caves or from simple surface solution. Advanced karst stages have broad lowland tracts caused by enlargement and coalescence of sinks and unroofing of caves and possess only much reduced residual areas recording the original surface. Streams in such a karst abandon portions of their valleys and disappear underground to follow cave routes more favorable for escape of their drainage and emerge as resurgences only in deep master-river valleys. The former cave population beneath such lowland tracts becomes greatly reduced, although the number of separated cavities increases through dismemberment of integrated cave systems. Surviving cavities in an advanced karst topography are most prominent in the residual hills.

Except for (1) the lack of short, dismembered surface streams, (2) the existence of sea-water cave pools, and (3) the almost complete marine submergence of the lowland tracts, Bermuda's solutionally made topography resembles mature or old-age karst. Even the subterranean streams of a karst topography are represented by the submarine connections of the tidal cave pools and by the salt-water "springs" in the islands' most nearly enclosed inland water body (Harrington Sound) when the oceanic tide is rising. The dune topography is younger than the karst and records a partial restoration of the calcium carbonate removed by this solution. These dunes have no known solution caves. Their rock is too porous for concentration of ground-water flow.

One solutional cave possesses a total vertical range, including the reported depth of its pool, of 90 feet. But most of the high cave chambers seen and traversed by a visitor, some even opening well up on a hillside, are only fracture openings caused by collapse of subjacent solutional chambers. Their vertical range is not to be imputed to the cave-making processes here considered any more than are the abrasionally made caves in wave-cut cliffs.

Bermuda has two regions of numerous cave fragments: St. David's Island, and the isthmus separating Harrington Sound from Castle Harbor. St. David's known caves all open in the cliffs of the eastern Atlantic coast. With one exception, the isthmian caves are largely still enclosed, and none opens on cliffs of the present shores. Besides these two cave regions, there are many cave relics, i.e., sea cliffs with shallow-roofed re-entrants and abundant old and corroded dripstone deposits in the concavities.

At least five caves open in the sea cliffs of St. David's between The Battery and the lighthouse. None can now be followed back under the hill beyond view of the opening because of dripstone barricades. One cannot even be squeezed into. Two have spectacular dripstone columns, ranging from 9 to 15 feet long from floor to ceiling and up to 2 feet thick. They are readily recognized from a coastal vessel. So closely crowded are they that one can scarcely pass between some. The heavy dripstone has been "dead" a long time, for much of its original translucent, lustrous onyx has been dulled, although the typical structures made by concentric enlargement have been preserved.

One of these St. David's caves is unique for Bermuda because it contains a pool of fresh water, a source for the natives when the rains fail. It is perhaps the only natural fresh-water pool in the islands. Only a water-tight seal of the pool's bottom can be responsible. This cave also has a rarity in Bermuda, a series of old rimstone dams stepping down *into* the cave from the entrance in the sea cliff and disappearing under the pool surface.

Another cave in the St. David's cliff has

blind pockets and a spongework of interconnected cavities in the top of its wall, possible only if the cavity was completely water-filled when their solution occurred. Present mouths of all these St. David's caves have been made by sea-cliff retreat. Altitudes of floors range from 20 to 40 feet A.T., and the seaward margin of the island when the caves were ground-water conduits must have been well out on the submerged shelf and close to the abrupt drop-off from depths of 10–25 fathoms to 200–300 fathoms. A water-table gradient of about 1 in 300 could have existed under these conditions.

There are 10 named caves in line along the Harrington-Castle Harbor isthmus and its landward extensions, a distance of about 3 miles. Each cave has concrete steps or walks for visitors, although only two are now operated as commercial caves. All these caves have tidewater pools, a feature possessed by no St. David's cave. The Admiral and Joyce caves are so close that a little quarrying in dripstone or fallen-rock blockades would undoubtedly open the former connections. Walsingham cave is so extensively collapsed that its lateral chambers now constitute nearly a dozen separate, partially roofed cavities large enough to enter. Tucker's Town Cave displays only a large vertical shaft nearly 50 feet high, heavily ornamented with great stalactites just inside the cavity which obviously conceal further extension back under the hill. Leamington, Wonderland, Admiral, and Crystal caves are entered from the hillslope approximately 100 feet above tide by way of huge cracks or fractures whose walls have separated in the settlement that made them. Admiral cave has a detrital cone of surface soil and multitudes of land-snail shells but no present opening above the cone. Admiral and Wonderland caves consist essentially only of fracture openings down to the tide pool. Only Joyce, Crystal, Castle Grotto, and Leamington caves show much chamber capacity that is clearly solutional in origin.

Two unnamed caves discovered in quarrying also lie in this line, one in Government quarry, the other in Wilkinson quarry. Both show marked failure of roof rock, one being entirely a fracture-made cavity which probably originated from the collapse of an underlying solution-made chamber. The tidal pool covering its floor shows that the solution cave lay well below present sea level.

The best display of a surviving solution chamber in Bermuda is in Crystal Cave, 120 feet below the discovery hole in the hillside. An artificial entrance, by ramp and stairway, leads down to a high narrow chamber wholly of fracture origin, and that, in turn, down to the long narrow tidal pool in the horizontal solutional chamber. The visitor walks nearly 200 feet on a pontoon-supported bridge for almost the full visible length of a pool, having head height of 8–10 feet and reported maximum depth of the pool below him of 80 feet. Great stalagmites stand in depths of 30 feet of sea water. Divers have found stalactites at depths of 60 feet still attached to the ledges from which the original dripwater fell. The tidal range in the pool is that of Harrington Sound 1000 feet distant.

Fracture as the cause of the upper, high-ceilinged chamber is further shown by the large angular blocks under heavy dripstone deposits on the footwall side of the steeply inclined passage. There are no solutional roundings or pocketings above the horizontal chamber of Crystal Cave, and there are but few fracture outlines in this lower chamber. Its ceiling rock is largely covered with dripstone growth but, where visible, is intricately pocketed in a way that only solutional attack on that ceiling could produce. This horizontal chamber of Crystal Cave, now closed by fallen rock at one end and barricaded at the other end by dripstone, is a part of a former ground-water conduit that ran tube-full when being developed. It is essentially parallel with the length of the isthmus and with a line connecting all the known caves of the district and the failed caves in the two quarries.

This interpretation is in complete disagreement with that of Swinnerton (1929), who thought the fracture chambers of the caves he saw were solutional consequences of rainwater descending along joints toward a water table lower than the bottoms of the pools. Good joint patterns of two intersecting sets are shown in the islands' marine limestones and probably were an important factor in determining the locations of ground-water flow, but the solutional caves that resulted are horizontally elongated. The fracture chambers show no relationship to such jointing, and no eolianite formation with or without caves has shown regional jointing of any consequence.

Indubitable cave records exist on sea cliffs of Harrington Sound, Castle Harbor, Bailey's Bay, and elsewhere. The caves are tide-level recesses partially obscured by extensive heavy stalactites and draperies on the underhang of cliff faces. Only the back walls of the chambers

thus recorded survive. Destruction of such former caves has been a part of the making of the sound or bay depressions, depths of which approximate those of the deeper cave pools of the isthmus.

Solution caves are known elsewhere on Bermuda, but few are of the magnitude of those described heretofore, and none has closely associated neighbors. All, however, are low in the islands' carbonate deposits, and all are in the Older Bermuda of Sayles. One, completely submerged but with stalactites, has been reported from dredging in Hamilton Harbor in 30 feet of water.

The vertical range of solution caves, 50 feet A.T. to 80 feet B.T., limits them to the older, lower rock formations and limits our speculations as to time and conditions of origin. The abundance of caves in the linear Harrington-Castle isthmus must have some genetic significance. Dripstone is growing in some caves, is submerged in salt water in some, and is old, dull, and deeply corroded in others.

There cannot be two different explanations for the salt-water submergence in Bermuda's caves. Whether one holds for cave origin above or below the water table of their time of development, that water table vanished as sea level rose after dripstone growth had become well advanced. Before the rise began, sea level had stood below the bottoms of all cave pools.

By the theory that descending water dissolved out the caves, the islands' water table was below pool bottoms when the cavities were being enlarged. By the theory here advocated, of cave origins below the water table, Bermuda's rock was completely saturated with fresh water up to levels at least 50 feet above the present sea level when cave-making occurred, and an additional episode of water-table lowering must have occurred after cave-making and before dripstone deposition began.

Crystal Cave's fracture-determined, nearly vertical cavity, totally lacking in solutional outlines and leading from the surface down to a solution-made horizontal cavity with spongework of minor holes dissolved out of the very ceiling rock shows that the idea of solution by descending water must be abandoned and the rival explanation adopted, (1) that a horizontally moving circulation in completely saturated rock made the lower chamber, and (2) that collapse of part of this original cave made the steeply inclined high narrow entrance route. Crystal Cave thus records every stage in producing the present caves of Bermuda: (1) ground-water circulation in rock completely saturated with fresh water, (2) lowering of the upper surface of that ground water to allow air to enter the cave for the first time, (3) beginning of dripstone deposition, (4) fracture of overlying rock as the now empty solutional cave began to collapse, (5) rise of sea level to submerge the earlier dripstone of the lower depths, and (6) continued growth of stalactites and continued subsidence of roof rock. Water descending through the overlying rock has done nothing in this cave except to reduce its earlier capacity as destruction of the early cave system progresses.

Origin of the Interior Basins

If Crystal Cave and its neighbors are of phreatic origin (*i.e.*, originated below the water table), they must be older than the subaerial and submarine topography of their environs. They could not conceivably retain a complete fresh-water fill today, even if there were no Harrington Sound and Castle Harbor depressions. How and when were these depressions made?

Cave failures recorded in the cliffs of Harrington Sound and Castle Harbor indicate that at least the marginal portions of these depressions are of postcave age and younger than much dripstone in these former caves. It is notable that the exposed old cave walls linger largely at the heads of small, rock-walled bays which open off the Sound and Harbor. Tucker's Town Bay has a narrowed entrance from the Harbor, steep walls with intricate ground plan along its western shore, and a marked increase in depth adjacent to these walls. On the walls hang submerged stalactites. The cliffs about this deep, narrow bay cannot be imputed to wave work. They are collapse features and require solutional removal of subjacent foundation rock. Nearby is Tucker's Town Cave in the slopes leading down to Cable Bay, the eastern part of Tucker's Town Bay.

Walsingham Bay's indentations are comparable shore-line irregularities and have closely associated Walsingham Pond and the many collapse ruins of the Walsingham Cave system. Close by is Leamington Cave, now almost entirely a fracture-determined cave that requires for its origin an ancestral solutional cavity below present tide.

Richardson Cove on Ferry Reach, a part of Castle Harbor depression, is interpreted as another shore-line indentation caused by cave failure. The evidence consists of a surviving

small cave opening in its slopes, a number of excellent showings of cave-onyx deposits, and some stalactites. The onyx ledges (flowstone) crop out on both sides of the cove and have been found on the slope of a closed depression just east of the cove itself.

The quarry wall above the cave discovered in the Government quarry operations is a founder breccia extending to the surfaces, but it shows no long open fissure leading up through the breccia. The cave has no marked display of dripstone. Its gable-shaped ceiling is best interpreted as an arch supporting fractured but unfailed rock above. The causal solution cavity that received the fallen rock in making this fracture cave was so far below tide that all collapse debris has gone out of sight in the depths of the floor pool.

Wilkinson quarry at the north end of the Harrington Sound-Castle Harbor isthmian extension offers an epitome of the theme of consanguinity of Bermuda's caves and drowned depressions. Two well-exposed cave walls here, one inside the active quarry, the other just outside, show fracture patterns, but both also have typical solution pockets penetrating back and upward in the native bedrock. Much old dripstone is present, supporting the argument for cave chambers once at this place.

In addition to these fractured solution chambers, Wilkinson quarry shows three very marked fissures parallel to each other and to the near-by shore line and extending from bottom to top of the quarry's lateral walls. Each is steeply inclined shoreward. Each is nearly to completely filled with cave onyx up to about 2 feet thick. Most of the onyx is banded parallel with the fissure walls. Long, narrow fracture caves apparently became filled about as rapidly as they were opened. The opening of the fractures therefore was a slow and long-continued process.

In midwidth of the quarry, the trace of one of these filled fissures contains soil detritus, bird bones, and quantities of shells of the land snail *Poecilozonites*, some embedded in the onyx. Comparable deposits have been noted for Admiral Cave and formerly existed in Government quarry. These fissure planes locally became narrow, elongated collapse sinkholes open to the surface. The discovery route to Crystal Cave is such a sinkhole, still open.

A clearly shown buried soil, under about 20 feet of later eolianite, crops out completely around the Wilkinson quarry walls. It is faulted down about 10 feet on the shoreward side of the quarry, the fault being also a tensional parting along one of the filled fissures. Rock in the downdropped block is considerably fractured and constitutes a founder breccia.

The three fissures parallel to the shore line, and the downthrown side of the faulted one clearly being toward the Ferry Reach depression, record massive slicing of the hillside that contained the cave noted. Only if the depression then existed could this have occurred. The indicated slowness of movement suggests that deepening of this depression continued during, and was the cause of, the settling of the hillside.

Probably the most spectacular sinkhole in Bermuda is at Castle Harbor Hotel near the south end of the isthmus and in the line of caves here considered. Its rim is nearly 100 feet A.T. and its depth about 50 feet. Its eastern slope is fairly gentle; the opposite side is a nearly vertical wall densely vegetated but showing solutional cavities near the bottom, in a pattern unlike that left by soil-water attack. Some show an upward trend of the cavity back in the wall. The sink lies in a sag between two hills 160 and 180 feet A.T. and has no adequate drainage area to justify the idea that descending rainwater made it. It is interpreted as a collapse sink and, by that interpretation, another large solution cavity must have underlain the site.

These caves and sinkholes are in limestone rock of two kinds, eolian and marine, their original textures densified and in part recrystallized. Sayles identified, in ascending order, Walsingham eolianite, Belmont marine limestone Devonshire marine limestone, and Pembroke eolianite. Although the eolian formations may never have completely covered the existing Bermudian land, marine limestone crops out in so many widely distributed areas, both coastal and interior, up to altitudes of 100 feet A.T., that little doubt can be raised that Belmont and Devonshire sediments once extended completely across the sites of all presently submerged areas, the sounds, harbors, reaches, and bays of the island configurations.[7] Thus all such depressions are the product of some erosional agent.

Eolianite structures show that effective winds on Bermuda have come almost entirely

[7] Lowenstam finds good evidence that the Devonshire limestone is a "draped" deposit. It is high only where high surfaces of older rock already existed to receive it and nowhere was ever 100 feet thick. The Belmont limestone apparently never lay higher than about 25 feet above present sea level.

from the open oceanic coasts and can be held a factor in making the depressions only as they may have piled up marginal-land areas. Shore agencies operating in these enclosed and partially enclosed basins may be widening them but are depositing detritus rather than removing any. Stream erosion is patently not a factor. Marine solution is out of the question. Thus by elimination, only one possibility remains: that the disappearance of three-fourths of an original Belmont-Devonshire marine cover has been caused by solvent action of ground water from the islands' own rainfall.

This possibility rises to the status of probability, if not certainty, when all the records of ground-water solution and consequent collapse are considered. To this category belong all the small bays of the interior water bodies, many of those on the open coasts, and all the channels and straits separating the many minor islands in the interior. The islands, peninsulas, and isthmuses are but partially submerged hills of that solutionally made topography.[8]

Maximum depth of the interior water bodies is now 10–12 fathoms and would undoubtedly be greater if no wastage of margining cliffs had occurred. Maximum known depths of cave pools is 60–80 feet, a comparable figure. A pronounced submerged shelf on the south and east coasts is about 10 fathoms B.T., and the extensive lagoon on the west and north is nowhere more than 10 fathoms deep. The idea that all this shallow margining ocean water covers most of a former, far larger island was clearly stated by Stevenson (1897), and accepted by Verrill (1902). Sayles added that such widespread emergence occurred several times. Swinnerton (1929), Bryan and Cady (1934), and others have accepted this, and it is an essential part of the present interpretation.

To that idea we have added two more. One is the picture of an island-wide body of underground fresh water at such times and of extensive cave-making below the surface of that ground water. The other idea is that, although some foundering of cave roofs may have occurred during the phreatic episode, most collapse took place during the slow rise of sea level and the concomitant subsidence of the water table. Removal of foundered roof rock was effected by solutional attack of rain to such an extent that the broader basins (St. George's Harbor, Harrington Sound, Castle Harbor, Great Sound) became uvala plains. However, these four large interior basins are not to be reckoned as produced by solution-subsidence from altitudes originally as high as the surviving Older Bermuda hills, 100 to 200 feet A.T. Such hills are relics of Walsingham dunes, in many places showing a paleosol beneath Pembroke additions. Their alignment in imperfect rows marginal to the land masses indicates enclosure, perhaps partial, of lowlands approximately comparable to the floor of the lagoon north of the present islands but diversified by a few low residual hills (islands) of the Older Bermuda.

Any solutional epoch must have been later than the deposition and induration of the rock containing the caves or constituting part of the hills surviving the solution and collapse. If there was but one such epoch, it followed Pembroke deposition and preceded the growth of the coastal dunes. It was presumably a glacial age of lowered sea level. Because there were four such ages during the Pleistocene, there may have been more than one epoch of cave-making. But the earliest apparently was post-Belmont.

Correlation of Soil-Making and Dune-Building with Pleistocene Eustatism

Early students, seeking to explain the interbedded soils and eolianites, simply hypothesized raising and lowering of the ocean floor on which the volcanic mountain stands. Heilprin (1889) saw a possible explanation in shifting sea levels, but Sayles was the first to see in that interbedding a record of glacial control of the oscillations. He believed the dune-making episodes were a consequence of lowered sea level and resultant exposure of the lagoon floor and seaward benches (inevitably covered with organic carbonate sand) to attack by the vigorous winds of a glacial age. Some of this sand, swept southward, came to rest in the eolianites he named. He thought soil-making occurred during the milder interglacial ages when the lagoon and margining benches were flooded, less sand was available, no eolianite deposits were made, and climatic conditions favored weathering.[9] He found enough sugges-

[8] Exception to this statement is made for ponds and marshes enclosed because of later dune growth and for the row of dune-relict islands nearly closing Castle Harbor's southern side.

[9] He was never clear on the subject of solutional degradation of this land, therefore gave its dominance no specific place in the eustatic alternations of sea level.

tions of successive soils to lead him to attempt correlations, "extremely hazardous" as he admitted, between Bermuda's climatic oscillations and the Pleistocene sequence on the North American continent. Almost every later writer on Bermuda's geological history has accepted his suggestions, and his correlations are widely quoted in textbooks and in other studies of Pleistocene climatic oscillations. The writer knows of but one dissident view, that of Fairbridge and Teichert (1953), in a paper on coastal eolian limestones of Western Australia.

Sayles assigned soil-making to interglacial ages with a high-level ocean and eolianite-making to glacial low ocean levels. The present study reverses this relationship and holds that a complete record of a high sea level would consist of (1) an eolianite, (2) a marine limestone, and (3) an eolianite. Soil-making would occur, of course, but only on surfaces not reached by these deposits. The only land record of a glacial low sea level would be residual soil and karst topographic features.[10]

The Bermuda dunes are coastal deposits, tied closely to their source of sand, the beach. Their fixation was prompt because of incipient cementation. They did not wander inland. The application of this principle is far-reaching.

Consider that an interglacial high-water level is beginning to subside as another glacial climate develops and the Pleistocene ice sheets grow. The zone of sand-making, the shore line, retreats down the emerging shallow-water bottom. If coastal dunes are formed from the sand exposed and beaten up by the waves, their zones of growth will follow down also, abandoning successive belts or leaving a general eolian sand cover. Prompt fixation by rain water follows down also, and these abandoned sand tracts shortly cease to move.

If this is correct, the exposed lagoon floor never became a desert of shifting sand swept by glacial winds. A dune belt possibly left behind as an interglacial high began subsiding would not receive increments during the subsidence, nor during the static glacial low level, nor during the rising-water stage that followed. The sand becomes promptly fixed: only constant wave attack and agitation will keep it loose enough to be blown. Even if this fixed sand, transgressed as sea level rises, becomes broken up into loose beach sand, it will not be until the new interglacial sea level reaches its high stage that any wind-blown sand will be aggraded into a permanent deposit.

In the time required for a complete eustatic cycle, what will be occurring on any eolianite deposited during the preceding high sea level and on sand left behind during the glacial lowering? Given time enough, whatever Bermuda's glacial and near-glacial climate may have been, weathering would take place on all this land surface. It would be at a maximum where the exposure time was longest. All authorities hold that pluvial climates prevailed beyond the limits reached by contemporaneous ice sheets. Therefore more rain would drench this exposed sand of the lagoon floor and the older land surfaces, therefore more solution of the surface sand would occur, and thus more insoluble substances would be produced and they would accumulate faster than when warmer, drier interglacial climates prevailed.

There can be no question that dune-making and deposition of eolian sand alternated in general with soil-making times when little, if any, sand deposition occurred. Either the sequence given herein is correct or soil-making must be considered, as Sayles does, as an interglacial procedure. If it was limited to interglacial times, it was contemporaneous with coastal-dune growth around the margins of that high-level sea. But the two best developed paleosols of the island record little introduction of sand until later in their long development. The roots of the lower of the two, the Shore Hills, go below present low tide in many places. Excavations at Ireland Island Fig. 1) have encountered it (or a still lower soil) 46 feet below sea level. Sand drift on shore did not occur at that time. It is not asserted here that eolian sand never was blown inland during a soil-making, glacial low-water stage, but that in quantity, such sand was inadequate to give a calcareous character to either Shore Hills or St. George's soil.

As already noted, a light red, highly calcareous soil zone without roots or a "base" on the north shore of Whalebone Bay, Ferry Peninsula, St. George's Parish, overlies Devon-

[10] R. V. Ruhe *et al.* have found mineral constituents in both Shore Hills and St. George's soils that defy an interpretation of derivation from either marine limestones or eolianites. They indicate that such minerals (gibbsite, silica, iron oxide, lateroid pellets, *etc.*) could logically be derived from the basement volcanic rock. Lowenstam found magnetite grains in some laminae of Belmont and Devonshire limestones. It would seem therefore that at earlier low sea levels, some of this basement was exposed to wave attack. The volcanic rock was reached in exploratory drilling at the Kindley Air Field (Castle Harbor), 90 feet B.T.

shire limestone and is buried under an eolianite. Fossil shells show that the beach sand of the upper part of the Devonshire grades shoreward from marine to nonmarine in a horizontal distance of only a few hundred feet. The land snails of the nonmarine phase continue up into the immature soil which in turn is buried by a thick eolianite. The soil must be Sayles' "accretionary" Harrington, and the eolianite logically must be the Pembroke. Thus it appears (1) that wind-transported sand was accumulating here even before the Devonshire sea had wholly withdrawn, (2) that the Harrington soil records only a brief pause in such accumulation, and (3) that the Pembroke is only the dune record of the same high sea level that had already left the Devonshire limestone of the section.

A closely similar relationship exists on the south end of Watford Island, Sandys Parish (Fig. 1). Truncated soil roots at tide level penetrate a marine limestone and are overlain by another marine limestone which, by paleontological criteria, is Devonshire. The upper limestone clearly grades up the slope into a massive, unlaminated eolianite with no trace of a Harrington soil between. Hence the eolianite is interpreted as being of Devonshire age, deposited when the sea of that time was beginning to withdraw. Logically, it should in turn pass upward into Sayles' Pembroke. One need only assume that, because of too rapid an accumulation of dune sand, an "accretionary" Harrington did not have the opportunity to form at this place.

Wilkinson quarry in slopes of the Older Bermuda, already noted, shows two eolianites with a separating paleosol, the total height above sea level not exceeding 60 feet. No marine limestone is found here or in the vicinity. A sinkhole fill exposed in the quarry wall penetrates through the upper eolianite and the paleosol. Great numbers of *Poecilozonites nelsoni* and bird bones and chunky and disseminated red clayey material are all cemented together in the fill with semitranslucent travertine.

If *Poecilozonites nelsoni* became extinct before Pembroke time, the upper eolianite must be pre-Pembroke in age. By Sayles' stratigraphy, therefore, it is Walsingham eolianite. The paleosol and lower eolianite then must be pre-Walsingham, and there is no place for them in Sayles' stratigraphic column.

By this present interpretation however, the lower eolianite can be considered as Walsingham and the soil can be Shore Hills if the upper rock is interpreted as a Devonshire eolianite. By this view, any Belmont that may have overlapped on the Walsingham was destroyed during the soil-making, and the marine Devonshire that theoretically overlapped this upper eolianite has also been destroyed in making the surface soil which here appears definitely more advanced than that on the later dunes of the island.

This surface soil should bridge all time since St. George's soil-making began. It, however, is on an Older Bermuda hill summit much broken down by subsequent cavern collapse. If a marked residual soil was ever developed here, excessive slumping has destroyed it.

The faulted fissure in Wilkinson quarry cuts the paleosol near the back wall of the quarry, and the downthrow, added to the seaward dip, brings the paleosol down to quarry-floor level. Thus the eastern part of the quarry's south wall has no buried soil horizon. But another faulted fissure, nearly perpendicular to the one described, bounded the south side of the quarry at the time of examination. Comparable flowstone travertine and enormous numbers of snail shells were associated with many reddish clayey chunks and much disseminated debris in the fissure fill. This residual material lay higher than the buried paleosol near by and must have fallen from a level higher than the present intersection of hillslope and quarry wall. Because the shells are of *Poecilozonites nelsoni*, the vanished overlying eolianite must have been older than the Harrington soil, and the chunks of clay are best interpreted as from the Shore Hills paleosol, a portion of which here was left high on the upthrow side back of the quarry wall by the downdropping of the quarry block. Otherwise, the chunks must be derived from a vanished St. George's soil, above a vanished Pembroke, and we must deny the extinction of *Poecilozonites nelsoni* after Harrington time.

Wilkinson quarry and the road triangle north of the Biological Station afford the only known sections where what is believed to be Shore Hills paleosol is sandwiched between eolianites. According to Sayles' stratigraphic column, this soil should be bounded below and above by marine limestones. But by the theory here advanced, eolianite equivalents of both Belmont and Devonshire marine limestones may exist below and/or above the limestones, recording wind-transported beach sand deposited just before the sea reached its recorded maximum in any one section and/or just after the beginning of the recession. If a site of eolian deposition lay above the reach of the mounting Belmont and Devonshire seas, two eolianites could have been left without a marine tongue between them.

Only the Shore Hills soil, if present, would define them as separate formations of quite different ages.

Still another Bermuda section is significant. Black Watch Pass, north of Hamilton, clearly exposes southward-dipping lee-slope dune strata beneath Devonshire marine limestone. The contact slopes seaward (north) and is clean and sharp except at the very summit of the Pass where confused bedding replaces the uniform structure and may record a beach deposit. In this lee structure, dipping southward away from the lagoon and beneath marine beds of gentle seaward (northward) dip, are the lee remnants of a Devonshire dune whose windward portion was destroyed as the sea crept up the slope.

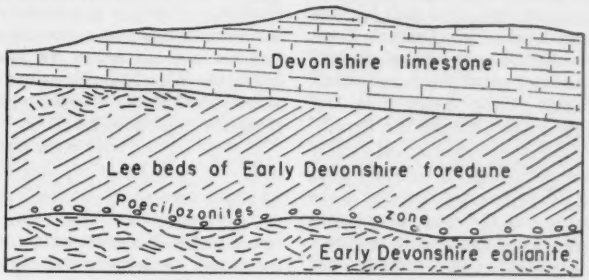

FIGURE 7.—DIAGRAM OF SECTION IN BLACK WATCH PASS, BERMUDA ISLANDS

The uniformly steep, parallel beds in turn rest on a body of eolianite whose bedding is exceedingly diverse in direction and angle of dip and strike and repeatedly cut by erosional surfaces between depositional units (Fig. 7). Such structures record accumulation on a windward slope. There is no trace of a soil between the two bodies of eolianite, hence they presumably are both records of the same high sea level, both Devonshire. It appears that beach sand became so abundant as the sea rose that a foredune grew in front of the slightly older deposit and finally overwhelmed it, only to lose its own windward portion as the sea continued to climb.

At the contact between the uniform lee-slope bedding and the underlying complexity of eolian stratification is a horizon especially rich in *Poecilozonites*. It suggests that a situation highly favorable for the snails existed here for a brief time, and that the shell zone is a time marker. It seems more probable, however, that the snail-favoring environment was limited to the base of the advancing front and was pushed up the older slope as that foredune grew. The snail zone does not mark a unit of time.

The persistent recurrence of a Harrington soil between Devonshire marine and Pembroke eolian deposits can hardly be explained by the picture here drawn for Sayles' two younger soils. If our contention that both Devonshire and Pembroke record the same interglacial high sea level (Pembroke being the dune sand of the retiring sea) is valid, the Harrington brown stain must mean an episode of minimum eolian deposition (and some wastage) immediately after the Devonshire sea had dropped below the present coast-line level, yet before the maximum of eolian accumulation during the late Devonshire-Pembroke epoch. Required for such an episode is a minor re-advance of the receding Devonshire strand line somewhere not far out on presently submerged Bermuda. The Harrington accretionary soil was developed during the first recession and became buried as the sea climbed part way back and its contemporaneous dune belt was extended inland as the Pembroke formation.

The glacial epoch following the Devonshire-Pembroke high sea level is recorded in the well-developed St. George's residual soil on Pembroke and locally on older rock. The Harrington minor marine recession and incomplete re-advance came early in this major sea-level subsidence. Had the re-advance never occurred, there would have been no Pembroke formation, and only the eolianite directly overlying Devonshire marine limestone and carrying the Harrington soil would record the early recession of the sea. The mature St. George's soil would occupy the Harrington position.

Possible correlation with the Pleistocene of the continent seems suggested by the occurrence of this interruption of oceanic lowering.

One asks, however, if our reversal of Sayles' sequence is correct, why there is no dune-building of consequence on Bermuda at present, a time of high sea level comparable to an inter-

glacial age. Sand of the same character as in the existing dunes is being made by organisms and by wave abrasion along the shores. But in only three places, Tucker's Town Beach, Elbow Bay Beach, and the shore along Chaplin, Stonehole, and Jobson bays, is beach sand being blown back on the land in conspicuous amounts.

Nelson (1837) noted that sand drift had begun about 70 years earlier near Tucker's Town and Elbow bays and had built a "sand glacier" at the bay. A house in front of this dune eventually became buried. These dunes were still active at the time of the CHALLENGER Expedition (1879), but the rate of growth had greatly diminished. Stevenson (1897) reported that little advance at Elbow Bay had occurred in the preceding 20 years. But the sand had reached 150 feet A.T. and showed an "evident tendency to consolidation". Verrill (1907) imputed the explosive dune activity to reckless deforestation and brush burning. He found modern sand drift to have reached 180 feet A.T. Today, Tucker's Town dunes and the blown sand at Elbow Bay are still active although much damped down by growth of vegetation, native and introduced. Some near-surface cementaton is observable at Tucker's Town.

Some sand from the beaches is being added to near-by land slopes without overwhelming the vegetation, but it is much less conspicuous. McGall's Hill, Smiths Parish, culminating in the seacliff called Spencer's Point, has a forested lee slope not far from the angle of stability. A pit in this slope shows white, friable, unlaminated "sandstone" containing an abundance of land-snail shells. This lee slope is growing from contributions blown up and over the cliff summit but accumulating too slowly to be conspicuous by dominating the vegetation.

The scarcity of active dunes today along the shores of a high sea level where, by our theory, dunes once grew may in part be a consequence of the island's present-day cliffs, whose magnitude and extent far exceed any cliffs recorded in the Older Bermuda's stratigraphic unconformities. With very little beach sand in front of the cliffs, and that more likely to be dragged off into deeper water than to be blown up over the cliff summits, no marked dune growth can be expected.

Marine terraces must be considered in this problem of correlation. Numerous students of land forms have described the Atlantic Coast of the southern United States, 600 miles distant from Bermuda, as possessing a series of old shore lines well above present sea level. More recently some students have reduced the number and envisioned the higher features as stream-made, therefore not precisely marking the sea level of their time. Two definite strand lines, with associated marine Pleistocene sediments on the seaward side, are widely recognized from Florida to New Jersey. The higher (Surry) is now 90–100 feet A.T. The lower (Suffolk or Pamlico) is considered the younger, and some interpret it as recording a Sangamon high sea level succeeding the Illinoian and preceding the Wisconsin glaciations. Others regard it as a record of mid-Wisconsin glacial recession. It stands 20 to 30 feet A.T.

If these records were made by a rise of ocean level due to deglaciation, they should occur on all stable coasts with favorable slopes throughout the world. On Australia, Europe, both coasts of the Mediterranean, and other places, somewhat comparable records have been reported as Pleistocene. Thus Bermuda, if on a stable ocean floor, should have received correlatable scorings and deposits.

Sayles (1931, p. 446) found a few benches facing the Atlantic and ranging from 8 to 25 feet A.T. He read them as wave-cut Pleistocene features and assigned their elevation to a very recent lowering of sea level.

Lowenstaim and the writer looked in vain for any shore lines higher than those Sayles found, any that would be comparable to the 90 to 100 feet A.T. Surry shore line on the Atlantic Coast of the United States. Considering the extensive cliffing on Bermuda's shores today, much of any record of successive abandoned strand lines may well have been destroyed, especially the lower ones. Also the solutional lowering that Bermuda has undergone may have obliterated them, or later advancing dunes may have covered them.

During any sea level higher than the present, Bermuda's extensive inland sea-water bodies should have embayed the older topography of the islands more than they do today. Marine sediments in these protected places should record some of the interglacial high sea levels. Here perhaps belong the Belmont and Devonshire limestones, as Sayles believed. Because they contain no fossils older than Pleistocene, yet are older than all Bermuda subaerial deposits except the Walsingham eolianite, Sayles properly considered them as early Pleistocene.

His correlation with North American Pleistocene, "exceedingly hazardous" as he admitted, includes both Belmont and Devonshire limestones and both Shore Hills and Harrington soils in the Yarmouth interglacial stage. Following are our objections to this correlation:

(1) Shore Hills soil roots come down to low-tide level of today. If these residual paleosols record interglacial climates as Sayles thought, they must coincide with high sea levels. But the Shore Hills sea was not as high as that of today's "interglacial" level.

(2) There is a marked unconformity between Belmont and Devonshire limestones which in some places includes a wave-made basal conglomerate of pebbles, cobbles, and worn shells, and a wave-made nip in the Belmont. The inland depression of Ferry Reach (Stokes Point and Mullet Bay) seems clearly to record extensive destruction of Belmont rock before re-occupation by the Devonshire sea. Adequate time for this subaerial reduction must be allowed while sea level was lower than today, presumably when Shore Hills soil roots were being made.

(3) Both limestones record a higher sea level than today, the Devonshire sea reaching at least 100 feet A.T. Assignment of adequate time for deposition of each of the marine limestones, for the intervening erosion, and for the shift of sea level from one extreme to the other demands that the Belmont and Devonshire formations should each be given interglacial rank and that the erosional interval with the Shore Hills soil-making should be assigned to a glacial low-water stage. Only thus can the succession of events in Bermuda's earlier stratigraphic history dovetail satisfactorily with the generally accepted sequences of Pleistocene eustatism.

(4) Lowenstam's discovery in 1957 of a marine member above Pembroke eolianite at Spencer's Point, Smith's Parish, carrying St. George's soil, corroborates the interpretation of the Whalebone Bay section. Neither section is theoretically complete, but the stratigraphic items are nicely interrelated for our preferred theory. The Harrington soil is present in both with Devonshire limestone beneath. Whalebone Bay's suggested record of a minor marine withdrawal for this soil to form close to the beach and of a return of the sea to produce the Pembroke eolianite is amplified at Spencer's Point by an actual marine member at the proper place. Absence of an eolianite above this marine member would mean either that none was deposited here or that St. George's soil-making destroyed it. Thus an oscillation of sea level during early Devonshire retreat is recorded in both sections. The Spencer's Point limestone is really a part of the Devonshire record.[11]

(5) Our favored scheme requires that the post-St. George's eolianites (Sayles' Warwick, Somerset, and Southampton) be considered as recording interglacial time, not as Wisconsin glacial in age. A balanced picture, however, demands marine limestone equivalents for these younger eolianites. Considering that these dunes stand close to the shore of today and many are being destroyed by wave attack, such limestones should still be below tide.

Thus the later interglacial floodings of Bermudian flanks have been less than earlier ones. The present flooding, interglacial in character if not in fact, also falls short of Devonshire and Belmont transgressions. This view is in harmony with the generally accepted sequence of decreasing altitudes reached by the successively later Pleistocene highs.

Apparently nothing in Bermudian geology can be dated from the Wisconsin low-water stage except inconspicuous solutional degradation, perhaps some cave enlargement, some soil-making, and the accumulation of peat in the larger marshes.

(6) Sayles knew of no eolianite accumulation from Walsingham to Pembroke time. This seems to have been his reason for grouping the two limestones and their intervening soil together as one interglacial stage. But we believe that eolian deposition on land coincided with marine deposition offshore and that an eolianite of Devonshire age (Whalebone Bay, Watford Island, Black Watch Pass, and Wilkinson quarry) exists exactly as our theory calls for.

No soil is known between Belmont and subjacent Walsingham. By our interpretation only a Harrington type "accretionary" soil would be expected there. Erosional unconformity between the formations can be imputed to advancing Belmont waves. Although no gradation between Belmont and Walsingham has been found, comparable to that of Devonshire age, the suggestion that Belmont and the higher, landward portion of Walsingham are essentially contemporaneous seems valid.

No peat has been found associated with either of the two paleosols nor with the immature soil patches which Sayles considerably overappraised. Knox (1940) found 42 feet of peat in Devonshire marsh, Devonshire Parish, the largest marsh on the islands, and reported that 97.7 feet of peat had been penetrated in adjacent Hamilton (Pembroke) marsh, in Pembroke Parish. Although the peat-containing depressions are elongated parallel to the northern shore and separated from it by a row of eolianite hills, both their depths and the occurrence of Devonshire limestone and of paleosols in the separating eolianite hills show that hills and marsh depressions alike are parts of the solution-made topography of Older Bermuda. The basins are not simple, dune-blocked, undrained sags.

According to our argument under the topic of caves, the Wisconsin low-water stage should have favored a high water table in the widely emergent island. But because of the already existing huge solution cavities now containing the sounds, harbors, and reaches, this Wisconsin water table would not have had the island-wide character of earlier ones. If the cavities were emptied as the sea subsided, the lowest peat in them would have been deposited during the rise from the Wisconsin low sea level. If the rate of that rise had outrun the rate of peat accumu-

[11] Lowenstam has not yet committed himself on this interpretation.

lation, these marshes would now be shallow peat-floored bays. Peat and cedar trunks dredged from Hamilton Harbor, Ferry Reach, Town Cut Channel, and Ireland Island are relics of vegetation whose rate of accumulation did not keep up with that of sea-level rise.

According to Kulp *et al.* (1951), the radiocarbon date of a cedar log dredged from reported depths of 10–20 feet in St. George's Harbor is 11,500 ± 700 years B.P., and peat from above the log is 7600 ± 600 years old. Kulp correlated the wood with the Two Creeks forest, Lake Michigan, of late Wisconsin age[12].

W. S. Newman has collected cedar wood and peaty material "apparently overwhelmed by a rising sea level" from borings at the tip of the peninsula between Castle Harbor and Ferry Reach. Depths were 62 and 72–74 feet B.T., and C^{14} ages, as determined by Lamont Geological Observatory, were greater than 37,000 years (*Reported in* Broecker and Kulp, 1957, p. 1325). Stratigraphic position was undetermined, but the peninsula itself is a part of Older Bermuda, and the depression therefore is a product of post-Pembroke degradation. Borings here also found silty carbonate material with Pleistocene fossils at 60 feet, C^{14} age of which was determined as greater than 33,000 years. Broecker and Kulp suggest that sea level was rapidly rising and "evidently this deposition did not occur during the decline of the last Wisconsin glaciation."

If the peat-containing basins of Bermuda retained any fresh water during glacial ages, peat deposits may have accumulated well above the then low sea levels. In this could lie an explanation for the very thick Devonshire and Hamilton marsh peat without marine intercalations. Their basal peat may be much earlier than that in their upper parts.

Kulp *et al.* (1952) have attempted to fix C^{14} dates for Bermuda events from studies of carbonate sand, the samples collected from Sayles' specified localities for his Pembroke, Somerset, and Southampton eolianites. They reported the ages of the Pembroke and basal Somerset as greater than 25,000 years, the uppermost Somerset as 21,000 ± 1600 and 21,300 ± 1600 years, and uppermost Southampton as 17,600 ± 800 years. These samples were taken essentially along the traverse which Sayles (1931, p. 397) said possesses "such relations as to preclude any possible doubt that each soil represents a distinct and separate horizon". However, this study and R. V. Ruhe's work have shown that no formational sequence above the St. George's soil exists along this traverse. Sayles defined the Somerset and Southampton units from widely separated, very limited, and very immature soil patches in the eolianite sands.

Broecker and Kulp (1951) revised their estimate of the age of Sayles' Southampton formation. A sample taken 3 feet, 4 inches below the top of the formation (essentially the present land surface) was greater than 30,000 years old instead of 17,600 ± 800.

Even if there were a clear order of superposition, none of these figures can be accepted because not all the carbonate sand of Signal Hill had been freshly made at the time of the dune's growth. An undeterminable fraction is reworked eolianite sand, and the ages reported are incorrect by an unknown amount.

If the limited coastal benches of Bermuda were correctly interpreted by Sayles as wave-cut (and they look the part), sea level has been 25 feet higher on the island at some time in the Younger Bermuda's history. Sayles (1931, p. 446) thought the benches later than all his eolianites, thus a record of a "very recent negative eustatic shift of sealevel". But their altitudes require that the large marsh depressions were flooded contemporaneously to a comparable depth, Pembroke and Hamilton becoming shallow bays and Devonshire an enclosed salt-water pond like Trott's or Mangrove of today. A record of this submergence should exist. It has never been found, and Knox (1940) was certain that no such interruption ever occurred in the growth of the Devonshire Marsh peat.

Instead of questioning the origin of Sayles' coastal terraces as wave-cut, it seems preferable to date them from the same high sea level that gave rise to the later eolianites. If they were made later than all dune-building, there should be an adequate record on the dunes as well as on coasts not overwhelmed by dunes or subsequently strongly cliffed. Only a few limited terraces are known, and these can be better explained as having escaped both burial by dune growth and erosional destruction because of the present cliffing.

Conclusion

It is still "extremely hazardous" to attempt correlation of Bermuda's Pleistocene history

[12] C. H. Smith, the engineer in charge of the dredging, insists that the depth at which the log was found was less than half the minimum listed by Kulp.

CORRELATION CHART

Postglacial	*High sea*	Shore-line cliffing Small dune growth Soil-making Peat formation Rain solution	
Wisconsin	*Low Sea*	Some blown sand Peat formation Soil-making Solutional degradation	Younger Bermuda
Sangamon	*High Sea*	Later eolianite (Warwick, Somerset, Southampton) of existing dunes and burial of St. George's soil Embryonic "accretionary" soils (Signal Hill, McGall's) Deposition of marine limestone, still submerged Coastal benches (Pamlico-Suffolk, 20–30 feet A. T. max.) Soil-making	
Illinoian	*Low Sea*	St. George's soil, "residual" Local high water tables Cave enlargement? Cave-collapsing and completion of major karst depressions Solutional degradation	
Yarmouth	*High Sea*	Spencer's Point marine limestone Pembroke eolianite Harrington "accretionary" soil Coastal benches cut in Belmont and buried by Devonshire Devonshire marine limestone and eolianite with burial of Shore Hills soil	Older Bermuda
Kansan	*Low Sea*	Shore Hills "residual" soil General high water table Cave-making and cave-collapsing Solutional degradation	
Aftonian	*High Sea*	Belmont limestone Walsingham eolianite	

with that of the continent. Borings and excavations below tide have repeatedly found eolian rock and red soils *in situ* far below present sea level. We are not justified in assuming the Walsingham to be the oldest eolianite on the volcanic platform nor the Shore Hills the oldest paleosol. Nor do we know positively that the Walsingham is Pleistocene. Since the bottom of the column cannot be adequately inspected, any attempted correlation should start from the top.

The theme of glacially determined eustatic sea levels probably will never be superseded and, whether or not our reversal of Sayles' sequence of cause and effect be accepted, the recurrency is there to be counted.

This study recognizes four times, including the present, of high sea level. Each is recorded, in only fragmentary fashion, by eolian and/or marine deposits. Fossils of the two marine formations do not yet make correlation with other Pleistocene formations possible. The islands have only a poor showing of old strand lines for comparison with the record on Florida and the Atlantic Coast farther north. In a still less satisfactory chronological record, times of glacial low-water levels are marked by paleosols, cavern solution, peat deposits, and submarine benches. Only two buried soils of advanced development are recognized. The number of cave-making episodes is unknown. Identification of submarine benches with Pleistocene

stages is one thing; establishment of each or any as a maximum low of a given glacial age is quite another matter.

A mid-Wisconsin recession appears in some correlation charts, four and even five Wisconsin substages in others. Bermuda has only three known low sea levels in her history, only four (including the present) high sea levels. The vertical range of each is either unknown or unidentifiable with a continental stage, durations are only loose estimates, and the base of the Bermudian Pleistocene is unknown. The correlation presented here, therefore, is very tentative.

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ANORTHOSITE-ADAMELLITE COMPLEX OF NAIN, LABRADOR

BY E. P. WHEELER, 2ND

1755, Abstract, line 2, *for* low, *read* high

ABSTRACT

The anorthosite-adamellite complex has invaded basement-complex gneisses which have a low Na_2O/K_2O ratio and show many features of the granulite facies. Ultramafic rocks of the Alpine type occur. Assignment of the metamorphic rocks to the Grenville Province is at least open to question. The anorthositic rocks are subdivided into three facies. A dark facies is characterized by dark plagioclase and olivine. A pale facies is characterized by pale plagioclase and a low content of hypersthene with thin exsolution lamellae. A buff-weathering facies is characterized by antiperthitic inclusions in plagioclase, more abundant pyroxenes with exsolution lamellae indicating inversion from pigeonite, and accessory quartz. There is an imperfect progression from the dark facies in the north and east through a central area of pale facies to the buff-weathering facies in the south and west. Adamellite margins are variable in character near anorthosite and in places show clearly intrusive relations. A short distance within the margin a fayalite facies appears. In it plagioclase and pyroxenes resemble those minerals in buff-weathering anorthosite. It is greenish gray when fresh but rusts readily. The fayalite facies is succeeded westward by a hornblende facies in which much of the hornblende is poikilitic. There is also a biotite facies with intrusive relations toward the fayalite facies. Possibly it is more abundant toward the west margin of the complex. Small intrusive bodies occur, in many cases in gneiss zones involved with the anorthosite-adamellite complex. Many of them show affinities with the adamellitic rocks. Some olivine gabbroic rocks may be related to the anorthosite. Variations in composition of rocks and minerals of the complex could result from repeated intrusion of magmatic material evolving through differentiation by partial crystallization, with the zone of intrusion migrating westward. Faulting occurred in the region, but field data are insufficient for evaluation.

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INTRODUCTION AND ACKNOWLEDGMENTS

New material from the Nain-Okhakh region of Labrador has accumulated since the writer's 1955 paper, so that a progress report seems desirable. The prospect of additional data from continuing field work in the area discourages more extensive treatment at this time. The data and ideas set forth in earlier papers (Wheeler, 1942; 1955) are taken as the starting point for this discussion.

A grant from the National Science Foundation has covered a part of the field and laboratory expenses, and a grant from the Penrose Bequest of The Geological Society of America provided some of the air photographs being used in the study. It would have been difficult or impossible to reach much of the area covered without the air transport provided by the British Newfoundland Exploration Company. Profs. A. F. Buddington and H. H. Hess have given valuable help and advice. Discussions with members of the Cornell Geology Department faculty have influenced the writer's ideas and conclusions. He wishes to thank all

these institutions and individuals and acknowledge his indebtedness to them.

Basement Complex

The anorthosite-adamellite complex is surrounded by and involved with rocks of the Canadian Shield basement gneiss complex. The character and history of these rocks is complicated and obscure. Kranck (1939, p. 17–18; 1953, p. 33–37) has summarized them as well as the available data will permit. Any granitization in the region under discussion has not involved large-scale development of K feldspar. The gneiss is predominantly gray, and pinkness is so uncommon that its occurrence is signalized in several Eskimo place names. Of 187 gneiss specimens collected between Hopedale (lat. 55° 30′ N.) and Okhakh Bay (lat. 57° 27′ N.) only 45 have K feldspar as an essential constituent, and in only 11 of these does K feldspar make up as much as two-thirds of the total feldspar. Where biotite occurs in gneisses that do not contain essential K feldspar there is rarely enough for the K_2O/Na_2O weight ratio to reach unity. A tendency to avoid collecting from coarse-grained simple pegmatites and to treat large granitic areas as intrusive rocks separate from the gneisses gives these data some bias, but the purpose of collecting specimens was to sample the range of the rocks in the region, and it is probably accurate to say that the gneiss series is sodic. This region must be added to the growing list of Canadian Precambrian areas in which the preponderance of gneisses with a high Na_2O/K_2O ratio poses a problem (Pettijohn and Bastron, 1959, p. 596). In this region there is no evidence to support Pettijohn and Bastron's conclusion (p. 598) that albitization has occurred. Local graphite or cordierite and the well-rounded forms of zircons in the gneisses suggest that they are at least in part of sedimentary origin.

From Davis Inlet (lat. 55° 55′ N.) to Okhakh Bay and inland locally to beyond long. 63° W., wherever specimens have been collected, many show mineral assemblages characteristic of the granulite facies. The critical association of hypersthene and K feldspar occurs but only rarely. The characteristic association of hypersthene and augite (denoting any member of the series $Wo_xEn_yFs_z$) is common. Garnet is uncommon in the area covered by Plate 1, but the prevalence of augite suggests that the rocks contain too much CaO for garnet assemblages to develop. Presence of hypersthene, olivine, antiperthite, or perthite was used as the criterion for assigning rocks to this facies, provided amphibole and biotite were no more than accessories. Fyfe *et al.* (1958, p. 234) mention olivine in magnesian assemblages of the pyroxene granulite subfacies, and Parras (1958, p. 13) mentions it in ultrabasic charnockitic rocks, which he includes in the granulite facies. The wide distribution of these characteristic assemblages indicates that the region as a whole has progressed to a stage of metamorphism beyond the amphibolite facies. In many specimens the content of dark minerals is too low to show diagnostic assemblages. Widespread presence of hornblende or biotite as major constituents, even with otherwise characteristic assemblages, suggests that parts of the area may not have progressed beyond the hornblende subfacies of the granulite facies (Fyfe *et al.*, 1958, p. 235), or that retrograde metamorphism toward the amphibolite facies may have occurred. Among the relatively few specimens from south of Davis Inlet examined by the writer none contained typical granulite-facies assemblages; this indicates a lesser degree of metamorphism to the south.

Bands and lenses of ultramafic composition are numerous in the gneiss; most are measurable in feet or inches, though a few are much larger. Their degree of metamorphism corresponds with that of the enclosing rocks, and they appear to be products of metamorphic differentiation, or premetamorphic members of the rock that have been disrupted to varying degrees by the metamorphism.

Another group of ultramafic rocks can be distinguished from these by: generally larger size, in many places measurable in tens or hundreds of feet; common occurrence of marginal shear zones; presence as major constituents of such hydrous minerals as talc, chlorite, or antigorite enclosing residual olivine and pyroxenes; local development of carbonate with refractive indices high enough for dolomite or ankerite; presence of actinolitic amphibole, and possibly of anthophyllite. Many of these minerals indicate a much lower grade of metamorphism than that of the enclosing gneiss. Foliation of the enclosing gneiss generally conforms to the outlines of the ultramafic bodies, which possibly tend to be ellipsoidal.

These characteristics suggest that the bodies are of the Alpine type, as concluded by Kranck (1953, p. 33–34) for a body at Hopedale which he calls synorogenetic. Hess (Personal communications) considers material from a body on

East Okhakh Island (just north of the map area of Plate 1) to be a typical Alpine type. Similar rocks occur at least as far north as Naghvakh Fiord (lat. 59° 02′ N.).

Marble bands are few and thin in the region, and recognizable quartzites are absent from the Archaean gneisses, so that they differ from the type Grenville rocks along the Ottawa River. They do show similarities to the northeast half to one-third of the Grenville province where "sodic paragneiss and amphibolite of obscure origin predominate" (Engel, 1956, p. 93). Association with anorthosite has also been considered suggestive of Grenville affinity. However, as Robinson points out (1956, p. 18, Fig. 2), the dominant trend of the gneisses in the Nain region is northerly in contrast to the northeasterly trends in the accepted Grenville province. Hess (1955, p. 396, Fig. 1) implies that ultramafic rocks of the Alpine type are not to be expected in the Grenville. Unless these conflicting lines of evidence can be harmonized there is insufficient reason for correlating the gneisses of the Nain region with the Grenville.

Anorthosite Complex

Abundant large fresh exposures permit subdivision of the anorthosite complex into three major facies: dark, pale, and buff-weathering. Plagioclase that is dark gray on both fresh and weathered surfaces and widespread presence of olivine characterize the typical dark facies. The plagioclase is less turbid than in the other facies, and antiperthitic inclusions are absent. It is generally more calcic, but refractive indices indicate that it may go as low as An_{48}. Pyroxenes generally occur as rims around olivine and do not show exsolution lamellae. The few olivines tested were about Fa_{30}. Analysis 1 (Table 1) is from a typical rock of the dark facies.

The pale anorthosite is characterized by marblelike paleness on both fresh and weathered surfaces. The content of dark minerals is generally low. In some areas they are localized to form single crystals or coarse-grained masses a foot or more across. Refractive-index determinations indicate that the plagioclase range is An_{47-60}; the higher values and variations in a single specimen are rare. The range in a much smaller number of orthopyroxene determinations is Fs_{39-45}. The orthopyroxene contains only thin exsolution lamellae, probably augite, parallel to crystallographic c. Evidences of hydrothermal alteration such as turbidity in plagioclase and alteration of pyroxene to pale-green amphibole are possibly most prevalent in this facies. Some of the fine-grained material in plagioclase looks like poorly formed antiperthite, and a little accessory quartz occurs in some sections. These might be additional products of the alteration, or they may indicate transition toward conditions of the buff-weathering facies. Analysis 2 (Table 1) is from a typical rock of the pale facies.

The buff-weathering facies tends to be buff or iron-stained on fresh breaks, although the surface may be bleached pale by humic acid. Weathering commonly causes it to disintegrate into a rusty gravel more like weathered adamellite than anorthosite. Refractive-index determinations indicate that the plagioclase range is about the same as that in the pale anorthosite. Blocky antiperthite inclusions occur in most specimens. Turbidity is not prominent in the plagioclase. In most specimens both orthopyroxene and augite are present and total more than 10 per cent. Subophitic texture is perhaps more common in buff-weathering anorthosite than in the pale facies. Orthopyroxene composition lies within the range Fs_{40-40}, with two exceptions. Near the adamellite contact (Puttualuk Brook, 1123-foot lake, lower end, north side, Lat. 57° 09′ N., long. 62° 42′ W.) hypersthene compositions of Fs_{60} and Fs_{68} were found. Augite exsolution lamellae in orthopyroxene identical with those described and figured by Brown (1957, p. 529–534, Pls. 15–16) as indicative of inversion from pigeonite to hypersthene are common in this facies. The prevailing orthopyroxene composition would require crystallization at about 1050° C. (Brown, 1957, p. 530, Fig. 5), assuming no differences such as water-vapor pressure that would materially alter the temperature of formation. This indicates a high-temperature magmatic origin for the facies. Accessory quartz is generally present as sinuous grains following the margins of other constituents and indenting them.

The dark facies differs from the Marcy anorthosite of the Adirondacks, because of its olivine content and the pale facies does not correspond to the Whiteface anorthosite since it forms cores rather than margins, is relatively low in dark minerals rather than high, and is comparatively lacking in foliation.

Chatoyant plagioclase occurs in each of the three facies and possibly constitutes the surest evidence that a given rock belongs to the anorthosite complex. Apparently it is least

1757, column 2, line 26, *for* Fs40-40, *read* Fs 40-47

common in the buff-weathering facies. Darker-blue shades appear to be more characteristic of the dark facies, and paler-blue or green shades are more characteristic of the pale facies.

Minute dark oriented rod or needle inclusions occur in the feldspars of all facies but appear to be incompatible with antiperthitic inclusions. Where both are present the dark inclusions are restricted to the interiors of grains and the antiperthite to the margins.

Bent twin lamellae and curved cleavage surfaces are common throughout the complex.

TABLE 1.—ANALYSES OF ANORTHOSITE AND ADAMELLITE

	1	2	3	4
	CHEMICAL ANALYSES			
SiO_2	48.90	57.11	65.04	68.95
Al_2O_3	22.78	26.46	14.18	13.12
Fe_2O_3	0.61	0.15	1.14	2.17
FeO	6.03	0.39	6.52	2.85
MgO	6.84	0.06	0.63	0.80
CaO	9.40	8.81	3.89	3.11
Na_2O	3.33	5.68	3.03	3.63
K_2O	0.72	0.97	3.58	2.90
H_2O+	0.45	0.16	0.29	0.24
H_2O-	0.15	0.00	0.06	0.05
CO_2	n.d.	n.d.	0.10	0.16
TiO_2	0.98	0.10	0.98	0.90
P_2O_5	0.04	0.04	0.35	0.34
MnO	0.03	0.01	0.10	0.11
BaO	n.d.	0.04	0.18	0.24
C	n.d.	n.d.	n.d.	0.10
S	n.d.	n.d.	0.05	0.10
Total	100.26	99.98	100.12	99.77
Less O S	100.26	99.98	100.10	99.73
Maximum grain in thin section	9 mm	> 6.5 mm	5.0 mm	7 mm
Weight of sample	small	378 g.	669 g.	684 g.
	NORMS			
Quartz		1.19	21.72	29.58
Orthoclase	4.45	5.73	21.17	17.14
Albite	27.25	48.03	25.63	30.70
Anorthite	44.76	43.78	14.52	10.95
Nephelite	0.57			
Corundum		0.03		
Olivine	18.42			
Diopside	1.36		1.91	1.39
Hypersthene		0.59	10.07	3.26
Magnetite	0.93	0.21	1.65	3.15
Ilmenite	1.82	0.19	1.86	1.71
Apatite	0.11	0.10	0.81	0.79
Calcite			0.23	0.36
Pyrite			0.09	0.19
Normative plagioclase	$Or_6Ab_{37}An_{57}$	$Or_6Ab_{51}An_{43}$	An_{34}	An_{28}
Modal plagioclase	An_{59}	An_{46}	An_{37}	An_{30}
Normative mol. FeO/MgO + FeO in ferromagnesium silicates	.29		.82	.43
Modal mol. FeO/MgO + FeO in olivine	.31		.86 ± .12	

TABLE 1.—*Continued*

	1	2	3	4
	MODES (in volume per cent)			
Plagioclase	82.7	99.75	40.7	36.2
K feldspar			21.9	26.6
Quartz			28.2	27.6
Olivine	11.5		1.6	
Orthopyroxene	0.8		<0.1	
Augite	0.6		<0.1	0.2
Hornblende	0.3		5.7	3.1
Biotite			0.9	1.3
Opaque	0.1	0.20	0.5	2.5
Apatite		<0.05	0.4	0.2
Zircon			<0.1	0.1
Spene				0.3
Secondary mafic	3.6	0.05		
Carbonate	0.5		<0.1	
No. of points counted	1541	1582	1297	1282

1. Specimen 2-349. Troctolitic anorthosite, 3212 P (Johannsen), dark facies, from Kighlakhpait Mountains: Lat. 57° 07.4′ N., Long. 62° 30′ W. Rockfall from cliff. M. G. Keyes, analyst

2. Specimen 2-1255. Anorthosite, 1212 P (Johannsen), pale facies, from Khingughutik Lake, north of biggest island: Lat. 57° 10.8′ N., Long. 62° 20.0′ W. Doris Thaemlitz, analyst

3. Specimen 2-1237. Ferrohortonalite-bearing hornblende adamellite, 227″/7′ P (Johannsen), from Effa Lake, east end: Lat. 57° 09.5′ N., Long 62° 49.0′ W. Doris Thaemlitz, analyst

4. Specimen 2-1173. Black ore-hornblende-bearing adamellite, 226″ P (Johannsen), from Angutausughivik Brook, southeast branch, second lake: Lat. 57° 07.0′ N., Long. 62° 05.0′ W. Doris Thaemlitz, analyst

The warped cleavage surfaces are particularly striking in the giant hypersthene crystals of the pale facies.

The changes in mineral composition and in the composition of the minerals in the three facies as shown by the above descriptions and by analyses 1 and 2 (Table 1) are what might be expected if they constitute successive stages of the feldspar and ferromagnesian reaction series (Mason, 1958, p. 124–126). The absence of well-defined change in the plagioclase composition from the pale facies to the buff-weathering facies is offset by increased FeO/MgO ratio in orthopyroxene and probably also in augite and by the increased prominence of K feldspar and quartz. Such a progression suggests that the three facies represent successive stages of magmatic differentiation.

The field characteristics of the three facies are not always sharply defined, so that distribution and field relations may be difficult to determine locally, even with good outcrops. The dark facies is most widely developed along the northeast and east sides of the complex, the pale facies in the central parts, and the buff-weathering facies along the west side. Sharply defined contacts between the buff-weathering facies and the pale facies occur locally, for example, in the region near lat. 57° N., long. 62° 30′ W. Here and elsewhere inclusions of the pale facies occur in the buff-weathering facies. Where the buff-weathering facies is foliated the foliation curves to conform with contacts and inclusions of the pale facies, indicating that the former has invaded and engulfed the latter. This may well account for some of the minor hydrothermal alteration observed in the pale facies, although such alteration occurs far from any known occurrence of the buff-weathering facies; this suggests that other causes are at least in part responsible for it.

Few contact metamorphic phenomena definitely attributable to the anorthosite complex have been found. Cordierite-hypersthene gneiss and local corundum in marginal gneiss on the north shore of the Kighlakhpait Mountains (lat. 57° 09′ N., long. 61° 35′ W.) indicate that

1759, Table 1, footnote 1, *for* Long. 62° 30′ W., *read* Long. 61° 30′ W.
footnote 2, *for* Lat. 57° 10.8′ N., *read* Lat. 56° 50.8′ N.
footnote 4, *for* 226″, *read* 227″

conditions of the pyroxene hornfels facies were attained at least locally at margins of the dark facies. No good contact phenomena have been found in gneiss adjacent to the other two facies. However, metamorphic phenomena of the hornblende hornfels facies (Fyfe *et al.*, 1958, p. 206) would be obscured by the advanced grade of regional metamorphism in the area.

Adamellite Complex

The description of the adamellite complex in the Voisey Bay area (Wheeler, 1955) applies in large part to the area covered by Plate 1. The new work in this area indicates that rocks grouped as hypersthene facies in the Voisey Bay area lack sufficient petrographic unity to be classed as a single facies. Their one common characteristic in addition to the general presence of orthopyroxene is occurrence at or near the contact between the adamellite and anorthosite complexes, so that they might be grouped as marginal variants of the adamellite. Such rocks occur in a narrow, irregular zone that separates the two complexes east to northeast from Effa Lake (lat. 57° 10′ N., long. 62° 44′ W.). A specimen from this zone is medium-grained ore-bipyroxene meladiorite with exceptionally well-developed basal exsolution lamellae in the orthopyroxene, which shows unusually strong dispersion, $\rho < \nu$. It might be taken for a high-mafic differentiate of the anorthosite complex with reduced grain size, and the rest of the zone has a similarly ambiguous character. However, its orthopyroxene is a little higher in iron (Fs_{74}) than that of any well-defined buff-weathering anorthositic rock, and it is more probably a marginal variant of the adamellite. The intrusive relation of the adamellite toward the anorthosite, established in the Voisey Bay area, supports this conclusion.

The fayalite facies of the adamellitic complex is well developed in the region between Effa Lake east end (lat. 57° 10′ N., long. 62° 50′ W.) and Umiakovik Lake (lat. 57° 23′ N., long. 62° 50′ W.), apparently forming a zone on the east side of the complex. Minute oriented dark rod inclusions, characteristic of plagioclase in the anorthosite complex, occur, but more sparingly, in this facies. Blocky antiperthitic inclusions, which made their appearance in buff-weathering anorthositic rocks east of the adamellite complex, become more abundant in this facies. Where orthopyroxene occurs in this facies it contains basal augite exsolution plates like those in the buff-weathering anorthositic rocks. A specimen of buff-weathering noritic anorthosite from north of the 1123-foot lake at the head of Puttualuk Brook (lat. 57° 08′ N., long. 62° 42′ W.) contains 5 per cent quartz. Thus there is a petrographic transition between the two rocks.

The hornblende of the fayalite facies is olive green (Z = 5GY5/6), coarsely crystallized and nonfibrous, and has sharp contacts with adjacent minerals. There is no obvious reason to doubt its primary nature except for the large number of associated minerals, which is characteristic of this facies, as shown by mode 3 (Table 1) and other modal analyses (Wheeler, 1955, Table 3, p. 1040). This characteristic suggests incomplete magmatic reaction.

Analysis 3 (Table 1) is a better sample of possibly more typical fayalite-facies adamellite than either of the analyses given in the report on the Davis Inlet area (Wheeler, 1955, Table 7, analyses 3, 4, p. 1058). The norms indicate that its composition lies between those two except for its more calcic normative plagioclase.

The small amount of pyroxenes and olivine in the mode indicates that the rock is approaching hornblende-facies rock. Comparing the analysis with one from the hornblende facies (Wheeler, 1955, Table 7, analysis 1) shows that the differences are what might be expected if the hornblende facies represents a slightly more advanced state of differentiation.

Olive-gray color of fresh rock is proving to be a good criterion for identifying the fayalite facies and the marginal variants of the adamellite complex, which are finer-grained. On the basis of the change from olive gray to pale gray, most of the rock around Effa Lake belongs to the hornblende facies. Favorable exposures for studying the relationship between the two facies have not yet been encountered.

The biotite facies occurs around the south and west sides of Umiakovik Lake, and a well-defined intrusive contact between this rock and older rock of the fayalite facies has been traced for about 2 miles on the south side of the lake.

Cordierite gneiss float increases westward in the Effa Lake region, indicating that the adamellite complex has produced contact metamorphism on its west side in this region similar to that found in the Tessiuyakhsoakh area to the south (Wheeler, 1955, p. 1055–1056).

Minor Intrusive Rocks

Numerous small intrusive bodies occur near the anorthosite-adamellite complex and associated with the gneiss zones that taper into the

complex. They are petrographically similar to the rocks of the adamellite complex and may be correlated with its facies and variants. Analysis 4 (Table 1) shows the composition of rock from the interior of one of the larger isolated masses. It resembles an analysis of hornblende-facies adamellite from the Davis Inlet region (Wheeler, 1955, No. 1, Table 7, analysis 1) except for greater oxidation of the iron, more calcic plagioclase, and unusually high content of BaO. Graphite has been identified or suspected in several rocks associated with the anorthosite-adamellite complex. Generally there has been some indication of contamination by paragneiss, even in rocks that show igneous characteristics. The carbon content of analysis 4 (Table 1) is unexpected, and no contamination is indicated in this case.

Numerous smaller bodies are generally involved with the narrowing ends of the gneiss zones in the region north and south of Tikkoatokhakh Bay (lat. 56° 42′ N., long. 62° 15′ W.). Their affinities are more uncertain. Many are medium-grained monzonitic or tonalitic rocks in which mesoperthite is the most prominent feldspar. High-iron olivine is present in some. Possibly most of them can be correlated with marginal variants of the adamellite. Some of the coarser olivine gabbroic rocks northwest of Nain (lat. 56° 40′ N., long. 61° 45′ W.) seem more closely related to the anorthosite complex.

There is no evidence to date that contact metamorphism exceeded the hornblende hornfels facies even close to the margins of the larger minor intrusions. Decussate clusters of biotite and green actinolitic amphibole occur with intermediate plagioclase (An_{30}) in gneiss adjacent to the Angutausughivik body (lat. 57° 09′ N., long. 62° 10′ W.) and probably resulted from contact metamorphism of this grade. Epidote, chlorite, and accessory carbonate in these rocks are probably the result of late-stage hydrothermal activity. A little barite accompanying these hydrothermal minerals was suspected before the high BaO content of analysis 2 (Table 1), from this intrusive, had been reported.

Structure

The clearly defined intrusive relation of the adamellite to the anorthosite noted in the Tessiuyakhsoakh region (Wheeler, 1955, p. 1047–1048) does not appear to continue into the area covered by Plate 1. The evidence for petrographic gradation between the two complexes has been given above. Considering the igneous complex as a whole, there is a systematic gradation from olivine gabbro and troctolite in the east and northeast through the less calcic pale-facies anorthosite to the buff-weathering facies with increasing iron in the mafic minerals, followed westward by the transition from the buff-weathering anorthosite to the fayalitic adamellite and thence westward successively to hornblende adamellite and biotite granite. Exceptions and irregularities occur, but they do not appear to be so significant as the systematic progression.[1]

Unfortunately no structural evidence can be found to support the hypothesis that the whole igneous complex represents a layered series. Foliation is rare if not absent in the adamellite complex. It is very unevenly developed in the anorthosite complex and rarely shows low dips except in the northeast lobe (Wheeler, 1942, p. 637–638). Observations on foliation have not been systematic enough to permit reliable generalization, but the available data give the impression that foliation in the anorthosite complex is best developed near margins and gneiss zones and dips steeply toward them. The over-all pattern of structure and composition could be produced by repeated intrusion of magmatic material evolving through differentiation by partial crystallization, with the zone of intrusion migrating westward. Irregularities in the pattern would result from individual intrusive episodes breaking out of the current zone of injection.

Glaciation has brought out many striking linears in the area. Some appear to be the result of dikes, and others no more than zones of closely spaced joints along which no major displacement can be detected. Rarely, as in places along the Nakharvik Brook linear (lat. 57° 21′ N., long. 62° 10′ W.), mylonite zones give clear evidence of faulting.

Exposures are lacking along what may be the major fault linears of the area: Tikkoatokhakh Bay (lat. 56° 44′ N., long. 62° 15′ W.) and the valley west from it, and Nunaingoakh Bay (lat. 56° 36′ N., long. 62° 00′ W.) and the valley west from it. Detailed mapping has not progressed to the point where dislocations are unequivocally demonstrated along these linears,

[1] Subsequent field work on Khingughutik Brook headwaters (Lat. 57° 15′ N., Long. 63° 31′ W.) shows that the distribution of rock types is more complex than this simple outline indicates. The biotite facies of the adamellite is insignificant in this area, and several masses of anorthositic rock occur; one belongs to the dark facies.

but the available data can be interpreted as indicating left-hand displacements of 1 or 2 miles.

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BULLETIN OF THE AMERICAN GEOLOGICAL SOCIETY OF AMERICA
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CORRELATION OF THE PERMIAN FORMATIONS OF NORTH AMERICA

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ABSTRACT

The chart (Pl. 1) indicates the present stratigraphic classification of the Permian rocks in each important area of outcrop in North America and the time relations of the deposits in the several areas as now understood. Annotations in the text suggest the evidence for many of the correlations and point out unsolved and controversial problems.

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INTRODUCTION

This is Number 7 of the series of correlation charts prepared by the National Research Council's Committee on Stratigraphy (Dunbar *et al.* 1942, p. 429–434).

A preliminary draft of the chart was prepared soon after the committee was organized in 1940, but because of many unsettled problems its publication has been long delayed. Meanwhile rapid progress has been made in Permian stratigraphy, and the chart has been repeatedly revised. Many uncertainties still remain, but it is hoped that this report of progress will form a useful base for future investigation.

Time lines run horizontally across the chart; vertical shading indicates hiatuses; the many question marks indicate uncertainty as to the exact position of boundaries. Numerals in the box at the bottom of each column refer to corresponding items in the bibliography, and the

Editor's Note: In this paper we have departed from Bulletin style and followed the Committee Chairman's preference in the capitalization of time and time-rock units and in the spelling of redbeds as one word.

numerals in the Index of stratigraphic units indicate the columns in which each formation appears. The annotations, numbered to correspond to the several columns, are used either to indicate the basis for the correlation or to explain alternative views.

The Chairman has prepared the Introduction and has collated the information contributed by members of the committee as it appears in the annotations. Wherever conflicting views could not be reconciled, an effort has been made to present the problem and to indicate the need for further research.

The Chairman wishes to acknowledge the major contributions made to the chart by Philip B. King, both through his personal knowledge of the Permian deposits of Texas and New Mexico and his contacts with members of the U.S. Geological Survey who have recently been working in the Western States and Alaska.

In addition to members of the Committee, the following have made significant contributions to the chart by generously contributing their own personal comments which appear in the annotations: H. L. Berryhill, Donald W. Boyd, Carl C. Branson, T. M. Cheney, R. L. Clifton, E. R. Cressman, Wilbert R. Danner, Ronald K. DeFord, George Dixon, Helen Duncan, J. Thomas Dutro, W. M. Furnish, Mackenzie Gordon, Philip T. Hayes, Lloyd G. Henbest, Joseph M. Hoare, the late J. Brookes Knight, Ernest H. Lathram, E. K. Maughan, Daniel F. Merriam, V. E. McKelvey, Siemon W. Muller, Steven S. Oriel, W. W. Patten, Jr., P. E. Playford, Charles A. Repenning, Charles Ross, Robert Roth, Floyd Sabins, Robert Scholten, Norman J. Silberling, I. L. Tailleur, Wm. H. Taubeneck, Curt Teichert, C. W. Tomlinson, Willis Tyrrell, and Clyde A. Wahrhaftig. Of course we are also indebted to all those whose published works have been drawn on for information.

During the course of this work three members of the committee have been lost by death— G. E. Condra, John B. Reeside, Jr., and James Steele Williams.

Founding of the Permian System

The Permian rocks on which the system was founded occupy a vast structural basin west of the Ural Mountains, measuring about 700 miles from west to east and 1000 miles from north to south. This region is divisible into two major structural elements, the Russian Platform and the Uralian geosyncline. Over the broad platform the Carboniferous and Permian strata are nearly horizontal and of moderate thickness, but as they pass eastward into the geosyncline the Permian rocks thicken greatly and undergo rapid facies changes. It was here, along the western border of the Ural Mountains, that the Permian System was established.

Murchison visited this region during the summers of 1840 and 1841, primarily to see whether the Cambrian, Silurian, and Devonian systems, recently established by him and Sedgwick in England and Wales, would be recognizable and useful so far afield. By previous diplomatic negotiations he went at the invitation of Czar Nicholas I, and all facilities for travel and guidance were arranged by Count de Cancrine, the Imperial Minister of Finance. In this journey he had as colleagues the French paleontologist, Count de Verneuil, and the Russian geologist, Count von Keyserling. Arriving in Moscow early in the summer of 1840, Murchison and his colleagues were cordially received and placed in the hands of Lieutenant Koksharof, a trained geologist from the Imperial School of Mines. This first summer was devoted largely to the lower Paleozoic rocks along the northwestern border of the Russian Platform, but it also included a reconnaisance trip up the Dwina River into the Permian Basin. The next season (1841) began with a traverse eastward from Moscow along the Volga River to Kazan and thence eastward to the Ural Mountains, followed by several traverses of the Uralian geosyncline from Orenburg at the south to the Timan Arch at the north.

Before leaving Moscow, late in the fall, Murchison wrote a report to be laid before the Czar, presenting his interpretation of the geology of Russia, accompanied by a geologic map and a cross section from St. Petersburg to the Sea of Azov. In addition, he addressed to Fischer de Waldheim, President of the Academy of Sciences at Moscow, a letter proposing the Permian System. Returning home he published this letter in the Philosophical Magazine (Ser. 3, v. 19, 1841, p. 417–422). This brief statement constituting the original definition of the Permian System is as follows:

"The carboniferous system is surmounted, to the east of the Volga; by a vast series of beds of marls, schists, limestones, sandstones and conglomerates, to which I propose to give the name "Permian System", because, although this series represents as a whole, the lower new red sandstone (*Rohte todte liegende*) and the magnesian limestone or *Zechstein*, yet it cannot be classified exactly (whether by the succession of the strata or their contents) with

either of the German or British subdivisions of this age. Moreover the British lithological term of new red sandstone, is as inapplicable to the great masses of marls, white and yellow limestones, and grey copper grits, as the name of old *red* sandstone was found to be in reference to the schistose black rocks of Devonshire.

"To this 'Permian System' we refer the chief deposits of gypsum of Arzamas, of Kazan, and of the rivers, Piana, Kama, and Oufa, and of the environs of Orenbourg; we also place in it the saline sources of Solikamsk and Sergiefsk, and the rock salt of Iletsk and other localities in the gouvernment of Orenburg, as well as all the copper mines and the large accumulations of plants and petrified wood, of which you [Fischer de Waldheim] have given a list in the 'Bulletin' of your Society (anno 1840). Of the fossils of this system, some undescribed species of *Producti* might seem to connect the Permian with the carboniferous area; and other shells, together with fishes and Saurians, link it on more closely to the period of the Zechstein, whilst its peculiar plants appear to constitute a Flora of a type intermediate between the epochs of the new red sandstone or 'trias' and the coal measures. Hence it is that I have ventured to consider this series as worthy of being regarded as a 'System'."

During the next 3 years Murchison worked over his notes and data preparing his great monograph, *The geology of Russia in Europe and the Ural Mountains* (1845) which included a more detailed account of the Permian rocks and was accompanied by a geologic map, in color, showing the larger features of the vast area traversed. A reader of this magnificent classic will find it almost incredible that Murchison and his colleagues could have gained such a clear insight into the major geologic features of so vast and area in two brief field seasons. The fact is that much of the geology had already been worked out locally by Russian geologists, and, using principles of correlation by means of fossils, which he had so successfully applied in founding the Silurian System, Murchison was able to synthesize all previous work and interpret it in the light of his personal reconnaissance.

Limits and Subdivisions of the Type Permian

Original Permian Rocks

To anyone familiar with the region, it is clear that the original Permian System, as conceived by Murchison, comprised only the rocks now included in the Kungurian, Kazanian, and Tatarian stages. (*See* column 82.) The thick mass of detrital rocks along the western flank of the Ural Mountains, later defined as the Artinsk Stage by Karpinsky, was referred by Murchison to the Millstone grit (Lower Carboniferous), and the limestones of the Ufa Plateau and the Timan Arch were considered Upper Carboniferous.

Artinskian Stage

The Artinskian rocks were described by Karpinsky in 1874 as a thick sequence of shales, sandstones, and conglomerates exposed along the west flank of the Ural Mountains, "as at Artinsk". Their faunas were later studied by several paleontologists, notably by Krotow (1885) who listed 293 species and considered them to be Late Carboniferous. In a beautiful monograph of the Artinskian ammonites in 1889, however, Karpinsky argued that they are more closely allied to Permian than to Late Carboniferous faunas. This reasoning may seem strange, since no ammonites were then known from the original Permian rocks. His reasons, however, were twofold: (1) the Artinsk ammonites were structurally more advanced than those known from recognized Upper Carboniferous formations, and (2) between 1841 and 1889 ammonite-bearing formations in several other parts of the world had come to be recognized as Permian, and the Artinsk faunas were correlated with them. In spite of this indirect reasoning and of Karpinsky's rather cautiously worded conclusions, the Artinskian Stage gained almost immediate recognition as a part of the Permian System, not only in Russia but in other countries as well. Thus the base of the Permian was lowered in its type region to the base of the Artinskian.

Sakmarian Stage

In the original statement in which Karpinsky proposed the Artinskian Stage and described its type section, he referred to a basal calcareous unit in the Orenburg region as the Sakmarian limestone, named for exposures alon the Sakmara River (1874, p. 268). After he transferred the Artinskian to the Permian, some students of the problem apparently thought he had intended to exclude the Sakmarian limestone, for in 1891 he returned to the problem and concluded, "Thus I must declare that I have never established a two-fold division of the Ural Carboniferous-Permian strata into Artinskian and Sakmarian stages. I have established only one, the Artinsk Stage, which I regard as completely developed in the basin of the River Sakmara" (1891, p. 194, footnote). In a com-

prehensive restudy of this region, however, Ruzencev (1936) proposed to subdivide the original Artinskian into two stages, restricting the name Artinskian to the upper and using the name Sakmarian for the lower, which he also included in the Permian. He has since described many ammonites from the Sakmarian (1956) and has shown that these beds also carry the fusulines of the "zone of *Schwagerina*" (*Pseudoschwagerina* of current usage), and that they are correlative with the Wolfcampian deposits of America. Thus the Sakmarian Stage came to be differentiated as the base of the type Permian not by lowering it below the Artinskian but by dividing the Artinskian.

Meanwhile the limestones of the Ufa Plateau and the Timan Arch along the western margin of the Uralian geosyncline had become the subject of an acute controversy. Murchison had assumed, without significant faunal evidence, that they were Upper Carboniferous. Late in the nineteenth century Tschernyschew secured large collections of brachiopods from these limestones that formed the basis for his magnificent monograph, *Die Oberkarbonischen Brachiopoden des Ural und des Timan* (1902). In this he seems to have taken for granted that all these limestones were Upper Carboniferous. This is really not surprising since he had almost nothing with which to make comparisons either in the original Permian of Murchison or in the Artinskian of Karpinsky where the facies is so different and brachiopods are generally uncommon. (An exception would be the Kazanian limestones along the Volga River, but these are much younger and carry a restricted brachiopod fauna.)

In the meantime, Fredericks (1928; 1932) had subdivided the limestones of the Ufa Plateau into four stratigraphic units, and Tolstikhina (1935) had worked out five distinct faunal zones. When Rauser-Chernoussova found that the next to the lowest of these zones contained *Pseudoschwagerina* (*Schwagerina* of the older literature) it began to be evident that the limestones of the Ufa Plateau, previously considered Upper Carboniferous, might be largely equivalent to the Sakmarian Stage. In preparation for the Seventeenth International Geological Congress, therefore, a conference of Soviet specialists was held in Leningrad in 1936 to decide whether to draw the Carboniferous–Permian boundary above or below the "Zone of *Schwagerina*." In view of divided opinion, final decision was postponed for further consideration at the Congress. During the pre-Congress field trip to the Permian Basin, opinion tended to crystallize in favor of the lower boundary. Following the Congress, the problem was reviewed for American geologists by Dunbar (1940; 1942). It is now the official usage of the Geological Survey of the U.S.S.R. to draw the base of the Permian below the Sakmarian and equivalent beds in the Ufa Plateau—*i.e.*, below the Zone of *Pseudoschwagerina* (Likharev, 1958). With this decision American geologists are in complete agreement. The Soviet geologists recognize only two series, Lower and Upper Permian, each of which includes three stages, as follows:

Upper Permian Series	Tatarian Stage
	Kazanian Stage
	Ufimian Stage
Lower Permian Series	Kungurian Stage
	Artinskian Stage
	Sakmarian Stage

The Sakmarian and Artinskian stages are thick and largely detrital in the geosyncline but extend far out over the Russian Platform in a calcareous facies. The Kungurian, however, is confined to the geosyncline where it attains a great thickness (up to 4500 feet) but is largely composed of salts, and includes the great potash salt deposits of Solikamsk. During its deposition the sea had withdrawn into the geosyncline so that a large hiatus separates the Upper from the Lower Permian on the Russian Platform.

Kazanian Stage

The Kazanian Stage is in the calcareous facies in the Kazan region which lies far out on the platform, but these marine beds change facies toward the east, passing into thick red sandstones near Perm. The nonmarine beds have yielded rich vertebrate faunas. The Ufimian Stage is not well established, and by many Soviet geologists it is believed to be only a lower eastern facies of the Kazanian.

Tatarian Stage

The Tatarian Stage consists only of nonmarine redbeds. It locally bears rich deposits of land plants and vertebrates. It originally included both Permian and Triassic redbeds. Of several distinct vertebrate faunal zones only the lower ones are Permian; the upper are Triassic.

In some respects the Permian Basin is an unfortunate type section. Only the Sakmarian and Artinskian stages yield normal and varied

marine faunas with ammonites and fusulines as well as bryozoans and brachiopods. Thus, like the American standard section, the type section affords no satisfactory basis for correlation of the youngest marine zones of the Permian System.

American Standard Section

General Discussion

The discovery of Permian fossils in America was first made known in 1858 when a small collection of invertebrates found by Major Hawn near the mouth of the Smoky Hill River in Kansas Territory was described by Swallow and Hawn and by Meek and Hayden. In the same year a small collection from the Guadalupe Mountains in west Texas was described by B. F. Shumard. Later in the year a section of 820 feet of Permian beds in Kansas was described by Swallow and Hawn. About 30 years later Cummins (1890; 1891) described the Permian section in central Texas and defined the Wichita, Clear Fork, and Double Mountain groups. Meanwhile Cope (1878) had described Permian vertebrates from the Clear Fork beds. When the U.S. Geological Survey was organized in 1879 it recognized the Permian as a distinct system (Powell, 1882, p. XLVIII), as did the Texas State Geological Survey in 1889 (Dumble, 1889, p. LXIX).

Meanwhile considerable uncertainty existed whether the Permian was a valid system or only a series of the Carboniferous System. Accordingly, in planning for the mapping program of the Atlas Folios, the Director of the U. S. Geological Survey in 1889 called an important conference to decide upon the classification to be used, and it was then decided to regard the Permian as part of the Carboniferous System (Powell, 1890, p. 56–77). Arguments supporting this view were summarized by Keyes in 1899. On the contrary, Chamberlin and Salisbury (1906, p. 619–677) in their great three-volume treatise on Geology treated the Permian as a distinct system, and this view was given added stimulus by the publication of Girty's monograph of the Guadalupian faunas (1908 [1909]) and Böse's work on the ammonites of the Glass Mountains (1917). The U. S. Geological Survey officially recognized the Permian as a system in 1941, and this is now the generally accepted in America.

The basal limit of the Permian remained uncertain, however, for many years. Beede and Kniker (1924) had proposed that the "Zone of *Schwagerina*" (= *Pseudoschwagerina* of modern usage) should be recognized as the base of the Permian, but while the problem remained controversial the U. S. Geological Survey classified these beds (the Wolfcampian Series) as "Permian(?)". Since 1951, however, the query has been dropped, and the Wolfcampian is now generally accepted as Permian by American geologists. The decision of the Geological Survey of the U.S.S.R., cited above, to include the Sakmarian in the Permian, thus means that the base of the Permian is now drawn at essentially the same horizon in the type region and in the American section.

In 1939 a committee was organized by the American Association of Petroleum Geologists to select a standard section of the American Permian and recommend a scheme of major subdivisions. The report of the committee (J. E. Adams *et al.*, 1939) noted that the Permian Basin of West Texas contained the most extensive and useful section known and proposed a subdivision into four series as follows (in descending order): Ochoan, Guadalupian, Leonardian, and Wolfcampian.

A comprehensive structure section across the Permian Basin was published in 1942 by R. E. King *et al.* Of the many published works dealing with this region the monograph on the Glass Mountains by P. B. King (1930) and R. E. King (1930), and those concerning the Guadalupe Mountain region by P. B. King (1942; 1948) and by Newell *et al.* (1953) are noteworthy.

Wolfcampian Series

The type Wolfcampian crops out along the face of the Glass Mountains for about 40 miles and ranges in thickness up to 600 feet or more. These beds were deposited along the flank of the rising Marathon Mountains; they show complex facies changes along the strike and include much limestone and chert-gravel conglomerate. They carry a rich and varied fauna of fusulines of which the zone fossil is *Pseudoschwagerina*. The associated complex of genera and species makes this one of the most easily identified and widely recognized stratigraphic zones in the upper Paleozoic rocks of the world. It is represented by the Sakmarian Stage of the U.S.S.R., the Schwagerinakalk of the Alps, the Taiyuan formation of North China, the Chuanshan of South China and Indo-China, the Sakamatozawa Series of Japan, and the Copacabana group of Bolivia and Peru. Throughout the Orient and in Bolivia and Peru these beds gener-

ally rest upon Mid-Pennsylvanian (Desmoinesian-Moscovian) formations.

Leonardian Series

The Leonardian Series has its type section along the face of the Glass Mountains where it includes about 2000 feet of beds characterized especially by rather primitive species of *Parafusulina*, by a considerable variety of ammonites of which *Perrinites* is noteworthy, and by numerous brachiopods of which *Institella* and *Dictyoclostus bassi* and *Aulosteges medlicottianus* are distinctive. Leptodids and prorhictofenids also become common here but range higher.

Guadalupian Series

The type section of this series is at the northern margin of the Delaware Basin where it attains a thickness of about 3000 feet and shows complex facies changes of impressive magnitude. The lower and middle parts of this series are characterized by large and advanced species of *Parafusulina*, and the upper part by the more specialized genus *Polydiexodina*. Among the ammonites *Waagenoceras* and *Cibolites* are most distinctive, while *Trimorites* and *Zenodiscites* are confined to its upper part. A great variety of brachiopods occur here; the ranges of the most important are shown in the panel near the left end of Plate 1.

Ochoan Series

This series has its type section within the northern part of the Delaware Basin where it attains a thickness of about 4500 feet and consists largely of saline deposits, chiefly anhydrite in the Castile formation and halite with interbeds of potassium salts in the Salado formation. No fossils are known from the series except for an impoverished and poorly preserved invertebrate fauna found in a thin dolostone bed in the Rustler formation. This fauna clearly proves that the Ochoan is Permian but affords no basis for correlation with other upper Permian formations. Obviously this is an unsatisfactory series for a standard section, but it is directly above the Guadalupian Series, thus proving that the Permian section extends far above the latter. If, as now seems probable, however, the lamination in the anhydrite records seasonal deposition, the rate of accumulation of the Ochoan Series was rather rapid, and the time represented may be shorter than the thickness of the Ochoan deposits would suggest.

George Cohee reports (letter of July 1, 1960),

> "On June 28 the Chief Geologist [of the U. S. Geological Survey] approved the recommendation of the Geologic Names Committee that a two-fold subdivision of the Permian system and period be adopted for use by the U. S. Geological Survey. The divisions (Lower and Upper series and Early and Late epochs) are to coincide as nearly as possible with those recognized in the type Permian and are to be drawn according to existing concepts of biotal correlation with the type section. The reference sequence for the United States shall be the Permian outcrops of northwestern Trans-Pecos Texas (Delaware Mountains, Guadalupe Mountains, and Sierra Diablo Mountains), where the approximate faunal boundary is taken as that between the Cherry Canyon and Bell Canyon formations."

Dunbar believes the faunal evidence would place the boundary lower in the section, approximately at the Leonardian–Guadalupian contact. This is also the opinion of the Russian geologist, Ruzencev (1956).

Criteria for Correlation

Representation on Chart

In the Permian Basin deposition appears to have been nearly continuous, and a wide range of facies occurs at every level. As a result, no simple succession of faunal zones seems to be recognizable. Accordingly the ranges of some of the most important genera and species used in correlation are represented in panels at the left end of the chart. The ammonites were arranged by Miller and Furnish, brachiopods by Cooper, and the fusulines by Dunbar. In the ammonite panel the ranges indicated are based on world-wide data, but in the brachiopod and fusuline panels the ranges are based on the American record only.

The difficulties of zonation are illustrated by the following discussion of the brachiopod ranges.

Remarks on the Brachiopods

By G. Arthur Cooper

The ranges of the brachiopod genera and species listed on Plate 1 must be regarded as tentative and not yet well tested. The Permian faunas of North America are not yet well known, and the few that have been described in some detail are from unusual facies. The best-known and most extensive monographs

are those of Girty on the Guadalupe region and of P. B. and R. E. King on the Glass Mountains. The former was a pioneer work based on very limited field work and incomplete collections. The faunas are in need of revision as shown by the collections made by Newell and his parties working in the Guadalupe Mountains.

Stehl's work (1954) on a small segment of the faunas from the Diablo Plateau shows clearly that much revision and further elaboration of these fossils are still to come. The same holds for King's work on the Glass Mountains. Extensive collecting in this region by Cooper and his parties since 1939 will probably nearly double the specific representation from these mountains.

Some areas of the American Permian have never been collected in detail, and we cannot write intelligently of ranges until the faunas of these regions are collected and described. The Permian faunas in Arizona, Nevada, California, and other western States are virtually unknown. Cooper's (1957) description of the Permian in central Oregon shows a fauna with Russian affinities.

Another point that should be borne in mind when considering the ranges given on the chart is the local nature of the ranges. They are good for North America only. Some of the genera listed on the chart as characteristic of one American division are well known outside the European or Asian correlates of the American division. For example, in North America *Muirwoodia* appears to be confined to the rocks of Word age (and Capitan age of Alaska) as now defined, but in Europe its range is more extensive, possibly even into Wolfcampian equivalents. The Sosio beds of Sicily, which are correlated with the Word, contain many genera that have never been seen in the Word of North America. Facies may be partly responsible for some of the discrepancies, but they cannot explain away all the difficulties.

The Guadalupe Mountains contain rich faunas from restricted types of facies, especially the reef facies. The Glass Mountains also contain some specialized facies: the Wolfcampian and Hess deposits in the western part of the mountains were formed near shore; the eastern part of the Wolfcampian beds are a near-shore facies. Reef faunas are apparently not preserved in the Glass Mountains. Shale and sandstone faunas of the Permian are not well known, as indicated by our lack of faunal information for the extensive Permian deposits in north-central Texas, Kansas, Oklahoma, and Nebraska. Normal marine limestone faunas are also not well known. Much is still to be done on the Hueco limestone and the limestones extensively developed west of Texas, in New Mexico, Arizona, Nevada, and California.

A few remarks are made on each of the genera listed in the chart, and the tentative and local nature of the ranges is suggested.

Anidanthus. This genus was described first in Australia where it appears in Middle Permian rocks. In North America it is common at the top of the Leonardian and throughout the Word formation. Girty lists it from the Capitan limestone. In Europe on the other hand it is found somewhat lower.

"Aulosteges" guadalupensis.—This is actually not a member of the genus *Aulosteges* but a new genus, *Rhamnaria*, related to Stehli's *Ramavectus* (1954). It is common in the Word of the Glass Mountains and in the Capitan of the Guadalupe Mountains.

"Aulosteges medlicottianus" King (not Waagen).—This is *Edriosteges*, not *Aulosteges*, and the species name also is probably incorrect. The species was described from India where it occurs in the Lower *Productus* limestone. In the Glass Mountains this type of *Aulosteges* is fairly common in the western facies of the Hess and through the remainder of the Leonardian. It has not been seen in the Word.

"A." tuberculatus King.—This is a very distinctive and large aulostegid which likewise does not belong to the genus *Aulosteges*, but to *Echinosteges*. In the Glass Mountains it is fairly common in Word limestones No. 2 to No. 4 of P. B. King (1930) and in the Guadalupe Mountains it occurs in the Getaway limestone.

Cancrinella phosphatica (Girty).—This is a fairly large and distinctive species having rather wide geographic distribution. It has been identified in Mexico, in the northwestern States in the Phosphoria formation, and in the Glass Mountains. In these areas it is confined to the higher Word and its equivalents.

Chonetinella.—I have not yet seen this genus in beds above the basal Hess or the lower part of the Bone Spring limestone, but it is a small shell and easily overlooked. The range here given should be regarded with suspicion.

Coscinophora.—This is not a well-known genus (Cooper and Stehli, 1955) and was described only a few years ago. It is a leptodid that differs from most of these peculiar brachiopods in having the lateral loops of the pedicle valve in the form of rows of beads rather than ridges. The brachial valve in consequence has the form of a flat sieve. This genus is common to abundant in the Glass Mountains where it

ranges from the basal Hess through the lower Word. In the latter it forms scattered biohermal masses.

Cryptacanthia.—This is a terebratuloid with a long loop and is best known in the Pennsylvanian. In the Permian it has been found in the lower Wolfcampian beds in Nebraska. It is probably the ancestor of *Glossothyropsis*, a Permian genus especially characteristic of the Word.

Ctenalosia.—This is a rare shell recently described by Cooper and Stehli (1955). It is, however, very distinctive because of its denticulate hinge—it is the only known productoid so provided. In the Guadalupe Mountains it occurs in the Getaway limestone but in the Glass Mountains it occurs in Word limestones No. 2 and No. 4 of P. B. King.

Derbyia cymbula Hall and Clarke.—This species is a distinctive biconvex type best known from Wolfcampian rocks of Kansas and Oklahoma. It has been identified elsewhere from the Wolfcampian in the Glass Mountains and north-central Texas.

Derbyia sulcata Walter.—This is one of several brachiopods found in the Rustler formation of Texas and thus the youngest known species of the genus. Other species identified by Walter occur in lower parts of the Permian and are thus not distinctive. These are: *Wellerella elegans* (Girty), *Composita* cf. *C. guadalupensis* (Girty), *Hustedia* cf. *H. meekana* Girty.

"*Dictyoclostus*" *bassi* McKee.—This species has been widely identified in rocks of Leonardian age. It is abundant in the Glass Mountains. The species however does not belong to the genus *Dictyoclostus* but is a quite distinctive new genus, *Peniculauris*, described by Muir-Wood and Cooper (1960, p. 278).

"*Dictyoclostus*" *huecoensis* R. E. King.—This species does not belong to the Mississippian *Dictyoclostus* but is a new genus, *Reticulatia*. The species seems also to be identical with *D. americanus* Dunbar and Condra and thus is a fairly widespread Wolfcampian fossil.

Diplanus.—This is a small streptorhynchid described recently by Stehli (1954). It is common in the Wolfcampian of the Glass Mountains but ranges still higher into the top of the Leonardian. It is known from the basal Bone Spring limestone of the Sierra Diablo. Cooper collected it also in bed 10 of the Gaptank formation, underlying the Wolfcampian and in the *Uddenites* zone of the Gaptank.

"*Echinoconchus*" *nevadensis* (Meek).—This is an unusual type of echinoconchid (*Bathymyonia*) fairly common in the Phosphoria formation and its equivalents in Western United States.

Fascicosta.—Rhynchonelloids with bifurcating ribs are unusual in any formation. This distinctive little shell, recently described by Stehli (1955), occurs in the Word (Getaway) and Capitan limestones of the Guadalupe Mountains.

Geyerella.—This is a poorly known genus having a world-wide range in the Wolfcampian but is less well known in younger Permian rocks. In the Alps it occurs in the Wolfcampian with *Scacchinella*, but the two genera occur in abundance also in the Sosio beds now dated as Word equivalents. Elsewhere in Europe and Asia it is not reported from higher rocks. In North America its range is misleading, but it is abundant only in the Wolfcampian and the basal Hess limestone of the Glass Mountains. Here it is an excellent guide occurring as a small form in the Wolfcampian but as an enormous species in the basal Hess and the overlying Leonard limestone No. 1. It is not seen in North America again until the Capitan formation where on Guadalupe Peak two specimens were found. The abundance in the Lower and lower Middle Permian make it a good guide, but it could cause confusion in the future if found in abundance in higher rocks.

Glossothyropsis.—In its robust and swollen pedicle valve and nearly flat brachial valve this genus resembles *Cryptacanthia* of the Pennsylvanian and Lower Permian, but the descending elements of its long loop are separated. The genus occurs as a large form in Mexico, as smaller species in the Sierra Diablo and Delaware mountains, and in the Glass Mountains. In the Glass Mountains it is rare in the Leonardian but more common in the Word limestone. It has not yet been reported from the Capitan.

Heterelasma.—This is another long-looped terebratuloid commonest in the Word but known from the Leonardian and the Capitan limestone.

Horridonia.—No members of this genus have been found in the United States south of the Canadian line although the name has been incorrectly used for several species. It does occur, however, in Alaska. It is characteristic of the high Permian and is found commonly in the Zechstein of Great Britain and Europe.

Institella.—The range of this distinctive frilled productoid is equivocal. According to present knowledge it is confined to the Leonardian above the Hess facies. To complicate this useful restriction, a new species occurs in

the Capitan equivalents in the Guadalupe Mountains. In Europe it occurs in the Sosio beds and in the Caucasus Mountains in probable Middle Permian-rocks.

Juresania.—This genus is common in the Pennsylvanian and lower Wolfcampian especially of the Mid-Continent region. I have not identified it in the higher Wolfcampian or in any higher Permian rocks. It has approximately the same range in Europe.

Leptodus.—In the Glass Mountains a great variety of leptodids occurs which will probably one day be made into several genera. In the Leonardian a form resembling *Keyserlingina* is common. *Leptodus* in the strict sense has not been found in the Wolfcampian.

Leiorhynchoidea.—As now identified it is characteristic of the Word and its equivalents in Texas, the western United States, and Mexico.

Licharewia.—This is an unusual type of spiriferoid, exceptional for the fact that it has a smooth fold and sulcus, a condition rare in spiriferoids above the Devonian. Members of this genus are now known in North America only in Alaska and Greenland. They are more common in Russia in the high Permian.

Limbella wolfcampensis (R. E. King).—Stehli (1954) proposed the genus *Limbella* which is a fine-lined, frilled aulostegid abundant in the Wolfcampian but ranging into the base of the Leonardian (Stehli, 1954). It also occurs in the *Uddenites* zone of the Gaptank formation.

Liosotella.—Anteriorly costate productoids common in the Word and higher in the Capitan.

"Marginifera" opima Girty.—This species occurs in both the Guadalupe and the Glass Mountains. Specimens from the Glass Mountains are not conspecific with Girty's species, but both forms represent a new genus, *Paucispinifera* (Muir-Wood and Cooper, 1960).

Muirwoodia.—In North America this genus ranges from limestones No. 1 to No. 4 of the Word formation. It is not listed from the Capitan formation but it occurs in high Permian faunas in Europe and Greenland.

Neospirifer costella R. E. King.—This is an easily recognized species that occurs above limestone No. 1 of the Leonardian and is fairly common near the top of the Leonardian.

Ombonia.—The Capitan species of this genus were referred to *Orthotetes* by Girty. In Europe the genus occurs in the high Permian (*Bellerophon* limestone), but in Italy it is also identified in the Sosio beds of supposed Word age.

Orthotetella.—This is a rare genus occurring in the Wolfcampian of the Glass Mountains but ranging into the basal Leonardian (Basal Hess and basal Bone Spring limestone).

Orthotichia.—King mistakenly refers several Leonardian species of this genus to *Rhipidomella.* The genus ranges into the Lower Word, but I have not seen it above that layer. It is especially common in the Wolfcampian where it is identified as *O. hueconiana* Girty (= *O. kozlowskii* King).

Parakeyserlingina.—This form is rare in the Wolfcampian of the Glass Mountains.

Paranorella.—This is a nearly smooth rhynchonelloid having a reversed fold and sulcus. It is known from the Las Delicias area in Coahuila, Mexico, but appears also in Word limestones No. 2 and No. 3 in the Glass Mountains of Texas.

Parenteletes.—This is a distinctive and valuable genus resembling *Enteletes,* but having the fold on the pedicle value and the sulcus on the brachial valve. It occurs in bed 10 of P. B. King (1930) of the Gaptank formation but ranges into the Wolfcampian where it is represented by gigantic forms. In Europe and Asia it occurs in Wolfcampian equivalents; were it not for its occurrence in the Pennsylvanian in Texas it would be an excellent guide to the Lower Permian.

Planispina.—This is a name proposed by Stehli for richthofenid-like shells from the basal Bone Spring limestone of the Diablo Plateau. The genus is also abundant in the Wolfcampian and the Hess limestone of the Glass Mountains.

"Productus" capitanensis Girty.—This is a peculiar productoid having the external appearance of *"Dictyoclostus"* but with prominent flanges across the ears on the interior of the brachial valve. This type of productoid occurs in the high Word and Capitan of west Texas and of Sonora, Mexico.

"Productus" paraindicus McKee.—This is a strongly costate productoid occurring in the high Leonardian and its equivalents. King called it *Productus indicus,* but it belongs to a new genus, *Rugatia* (Muirwood and Cooper, 1960).

"Productus" semistriatus.—No described genus will receive this species although it has been placed in *Chaoiella,* a Russian genus. The species is widespread in the Wolfcampian.

"Productus" signatus Girty.—This is a new genus of productoids, *Grandaurispina* related to *Cancrinella* (Muirwood and Cooper, 1960). It occurs in Word limestones No. 3 and No. 4.

Prorichthofenia permiana (Shumard).—A

fairly long and slender species characteristic of Upper Word and higher rocks.

Spyridiophora.—This unusual genus (Cooper and Stehli, 1955) appears first in the upper part of the Gaptank formation where it is rare. It is not common in the Wolfcampian but occurs in the higher parts of the sequence. It is quite common in the basal Hess and in the rocks through Leonard limestone No. 1.

Strophalosiina.—This is a peculiar and complicated genus related to *Aulosteges*. In North America it appears to characterize the Leonardian Series. It is known from the Glass and Guadalupe Mountains. In Europe it occurs in the Sosio beds (Word); it is also known in the Himalaya Mountains in Asia and in the Island of Timor.

Teguliferina.—This genus is common in the Gaptank but extends through the Wolfcampian into the basal Hess limestone.

Uncinuloides.—This is a costellate form of *Stenoscisma* with truncated anterior that characterizes the upper part of the Leonardian of the Glass Mountains.

Wellerella.—This genus is abundant in the Pennsylvanian and Permian. The species recorded on the chart appear diagnostic of their parts of the column: *Wellerella texana* (Shumard), *W. transversa* R. E. King, *W. swalloviana* (Shumard).

Brachiopod zones.—I have been unable to work out any brachiopod zonation comparable in restriction to that of the fusulines and ammonites. No genus occurring in the Wolfcampian is confined to that series. *Parenteletes* offered possibilities, but it occurs in the top of the Pennsylvanian as that period is now understood. This is true of several other genera. Even the rare forms do not offer any help. Of the common genera all have roots in the Pennsylvanian or descendants in the higher Permian.

The situation is the same for the rest of the Permian. The Leonardian might be called the "*Dictyoclostus*" *bassi* zone, but the lower Word would have to be included in the zone. This brachiopod seems to be coextensive with *Perrinites* which also occurs in the basal Word (No. 1 limestone of P. B. King). When the "*D.*" *bassi* type of productoid is described, it will make a useful zone fossil.

In the Guadalupian a number of productoids, not yet generically named, offer possibilities. Such is "*Aulosteges*" *guadalupensis* which is common in the Word and Capitan limestones. The zone, however, would be recognizable only in the West Texas realm. No known generic name now seems to offer possibilities for zoning this part of the Permian throughout North America.

Fusuline Faunal Zones

By C. O. Dunbar

The rapidly and progressively evolving fusulines are especially useful in zonation and correlation. Although *Triticites* ranges up from the Pennsylvanian into the Wolfcampian and finally dies out therein, a rapid evolution at about the base of the Wolfcampian gave rise to a coterie of related genera—*Schwagerina*, *Paraschwagerina*, and *Pseudoschwagerina*—that completely dominates the Wolfcampian faunas. *Paraschwagerina* and *Pseudoschwagerina* are confined to the Wolfcampian except for a single known species of *Pseudoschwagerina* recently found near the base of the Leonardian (Dunbar, 1953). *Schwagerina* continues upward into the lower 500 feet or so of the Leonardian where it is represented only by species not found in the Wolfcampian. *Parafusulina* appears low in the Leonardian and ranges virtually alone through the rest of the Leonardian and up into the Guadalupian. *Parafusulina* is distinguished from its ancestor, *Schwagerina*, by specialization of the septa in which the tips of the septal folds are resorbed, leaving open passages—cuniculi—through the septa. In the earliest species of Leonardian age the cuniculi appear only in the later whorls and are low and narrow. In time they appear earlier in ontogeny and become larger. On this basis Leonardian species can in general be distinguished from those of the Guadalupian. Since the evolution is gradual, however, no abrupt change marks the upper limit of the Leonardian. At the base of the Capitan limestone and its basin equivalent, the Bell Canyon formation, a still further specialization occurs in that a series of auxiliary tunnels appears. This characterizes the genus *Polydiexiodina* which here replaces and succeeds *Parafusulina*. In general the Guadalupian can be distinguished from the Leonardian also by the greater size of the species and by the appearance of microspheric giants which have never been found in the Leonardian.

Polydiexodina does not extend above the McComb tongue of the Capitan limestone, and the Lamar tongue bears a complex of minute and highly specialized genera of the subfamily Boultoniinae such as *Paradoxiella* and has yielded a single small species of the genus *Yabeina* (Skinner and Wilde, 1955), the only

species of the Neoschwagerinidae known in the Permian Basin of West Texas.

In western Canada and the Puget Sound region, where the neoschwagerines occur abundantly, *Yabeina*, the most highly specialized genus of the family, occurs in beds above those containing the more primitive genera *Verbeekina* and *Neoschwagerina*. The latter beds may be in part at least equivalent in age to the Capitan, and the zone of *Yabeina* may be the time equivalent of the Ochoan Series.

The fusuline ranges shown on the chart are based only on the standard section of the Permian Basin of West Texas.

Major Problems in Permian Correlation

Redbeds

First of the difficulties involves detailed correlation of the redbeds that are so widespread and range in age from earliest to latest Permian time. Although vertebrate fossils occur locally, the redbeds are largely unfossiliferous, and even where interbedded with fossil-bearing members of limestone or dolostone the faunas are commonly limited in variety and include forms of doubtful value for correlation. In most places neither fusulines nor ammonites occur in the redbeds, and brachiopods, if present, are limited to the most hardy and therefore the most ubiquitous and long-ranging types.

The redbeds commonly are a marginal facies bordering rising land masses, and they range up and down in the section with variations in the local environment. Except where they intertongue with marine formations they can generally be limited in position only between overlying and underlying formations that are dated. In some areas they cross the Pennsylvanian–Permian boundary without evidence of interruption. The Supai redbeds, for example, overlie about 900 feet of marine Wolfcampian to the west of the Colorado Plateau (Columns 20, 21, 29), but in the Grand Canyon area (Columns 46, 47) they descend to rest directly on the Mississippian and farther east merge into the Cutler redbeds which locally contain middle Pennsylvanian fossils (Henbest, 1948).

The Maroon formation of Colorado likewise varies greatly in thickness and probably ranges locally from Pennsylvanian to mid-Permian with no direct internal evidence of its age.

In the eastern part of the Colorado Plateau (Columns 54, 55) almost the entire Permian section is in the redbed facies (Cutler). Here the basal part (Rico formation) carries interbedded limestones with basal Permian fusulines, but otherwise the redbeds can be correlated only on the basis of broad regional relations.

Along the front of the Rocky Mountains and under the Great Plains much of the Permian is of the redbed facies. In Wyoming thin tongues of the Phosphoria complex, reaching far out into the plains, permit close correlation of part of the redbeds with that unit, but farther south and east the uncertainties are much greater.

Vertebrate fossils occur locally and are the chief basis of faunal correlation within the redbeds. The best-known faunas are in the Wichita and Clear Forks groups of north-central Texas (Romer, 1935), but important occurrences are now known in the Abo formation in New Mexico, in the Cutler formation in both Utah and Colorado, and in the Popo Agie beds of Wyoming, and others will doubtless be found in many other places as study progresses.

Great Nonmarine Sandstones

In the Rocky Mountain province the Permian rocks include such thick and widespread bodies of sandstone as the Weber, which Brill (1952, p. 823) has characterized as a facies probably varying widely in age but with little real evidence of its age at any single locality.

The Coconino is a great body of largely windblown sand without fossils except local footprints. In the Grand Canyon section (Columns 45–47) it is only a few hundred feet thick and is limited above by the Toroweap and Kaibab marine horizons, but to the northeast and east it thickens enormously, replacing the enclosing redbeds (Columns 51–54), and divides into two great units, the DeChelly and the Cedar Mesa sandstones, which are of Coconino facies but obviously quite different in age from the Coconino (Fig. 1). These have been placed in their approximate position on the chart on the basis of broad regional relations, but there is no faunal evidence as to where their limits would fall in any particular locality in terms of the standard time scale.

Alaskan-Canadian Faunal Province

Permian rocks are widespread, thick, and in part richly fossiliferous in Alaska, but they were deposited in a faunal province that probably was never connected with that of the standard section in Texas and New Mexico, and the faunal affinities are all with the Orient and with the Russian Permian. G. H. Girty, who reported on many collections for U. S. Geological

Survey parties, recognized their Permian age but, lacking Russian material for comparison, could make only tentative and commonly generic identifications. Thus far no monographic

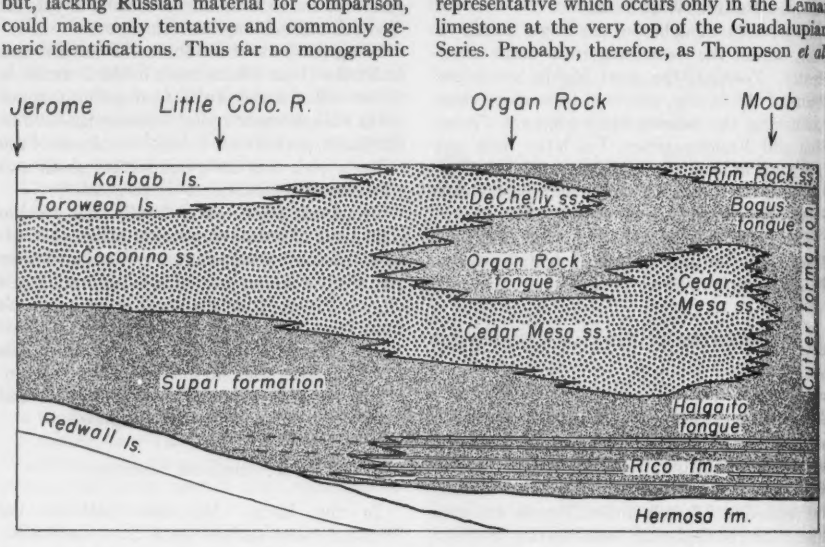

FIGURE 1.—DIAGRAMMATIC SECTION SHOWING FACIES CHANGES EAST OF THE GRAND CANYON REGION
Adapted from Baker and Reeside (1929) and Baker (1936; 1946)

studies of the Alaskan Permian faunas have been made, and no composite regional stratigraphic section has been developed. The placing and the ranges of the many local formations within the Permian System in Alaska therefore present many unsolved problems.

These difficulties will be overcome when the Permian faunas of Alaska are adequately studied. Fusulines are locally plentiful, for example, but only one species has been described (Dunbar, 1946). Brachiopods are present in great variety but have not been critically studied. Ammonites are probably present and will some day be a chief aid in keying the Alaskan section to other provinces.

The Alaskan faunal province extends southward into western Canada and even reaches into Washington (Column 12) and central Idaho (Columns 15 and 16). In the Kamloops region of southern British Columbia the Permian rocks have yielded a varied fauna of oriental neoschwagerines (Thompson and Wheeler, 1942; Thompson *et al.*, 1950) including such advanced forms as *Yabeina columbiana* and *Y. cascadensis*. Only a single small species of this genus has been found in the standard section of West Texas (Skinner and Wilde, 1955), a morphologically very primitive representative which occurs only in the Lamar limestone at the very top of the Guadalupian Series. Probably, therefore, as Thompson *et al.* (1950) believe, some of the beds in southern British Columbia and northern Washington are the marine equivalents of the Ochoan Series in Texas. However, in the Marble Canyon area of British Columbia, where these advanced neoschwagerines occur, the structure is so complicated that no satisfactory stratigraphic base has yet been established. If and when a good stratigraphic sequence is worked out here, and key zones can be found to relate it to the standard section in West Texas, it may be substituted for the Ochoan as the youngest Permian series in America.

Park City-Phosphoria Complex

This complex embraces the marine Permian rocks of a large area in Wyoming and Montana and a part of Idaho and Utah where it commonly rests on much older rocks. It was deposited in a rather specialized environment, and its faunas are limited in variety, having yielded only a few ammonites and no fusulines. Until after 1930 it was believed to represent a province geographically separated from the Grand Canyon region and from West Texas. Study of the few known ammonites (Miller

and Cline, 1934) and of the brachiopods (R. E. King, 1930) then led to a tentative correlation with the lower part of the Guadalupian Series (Word formation). It was therefore considered younger than the Kaibab limestone of the Grand Canyon region which is dated by fossils as Leonardian. This was clearly confirmed when the sections of Hobble Creek in north-central Utah (Column 29) were studied by Baker and Williams (1940) and the section in the Confusion Range of northwestern Utah (Column 28) was described by Newell (1948), since in both these areas a limestone lithologically like the Kaibab and carrying distinctive Kaibab fossils underlies the Park City complex.

Until recently therefore the Phosphoria was generally correlated, albeit on very limited faunal evidence, with the Word formation. In a recent critical study of the Confusion Range, Hose and Repenning (1959) have defined the Gerster formation, which they correlate with the Franson member (facies) of the Park City-Phosphoria complex. The Gerster formation here carries a richer brachiopod fauna than the Franson member farther east, and this fauna Mackenzie Gordon correlates with others in the west that include ammonites of Capitan age (Repenning and McKelvey, personal communication). Accordingly McKelvey *et al.* have extended the range of the Phosphoria and its equivalents to correlate with the entire Guadalupian Series.

Since tongues of the marine Phosphoria extend far eastward into the redbeds of Wyoming and South Dakota (Columns 36–39) these redbeds are keyed to the Phosphoria, and the correlations still farther east and southeast in Kansas and Nebraska are tied to this standard. Dating of the Gerster formation in the Confusion Range is, therefore, a key to a much wider region.

Ochoan Series

The Ochoan Series is confined to the Delaware and Midland basins where it reaches a maximum thickness of about 4500 feet and consists largely of saline deposits. As it is almost barren of fossils, it is an unsatisfactory unit of a standard section. This was recognized when it was proposed as a post-Guadalupian *series* of the American Permian (Adams, *et al.*, 1939). Nevertheless is constitutes a major unit of this, the longest and most complete Permian section known, and its relation to the underlying units is clear. The alternatives in 1939 were (1) to include these saline deposits in the Guadalupian (without fossil evidence and in spite of a profound change in regimen), (2) to set up a provisional *series* to embrace them, or (3) to choose a post-Guadalupian standard series from some other remote region.

When proposed, the Ochoan Series was not certainly known to be Permian rather than Triassic, and it was so dated on general regional relations. Distinctive Paleozoic fossils were later found in thin dolostone beds in the Rustler formation (Donegan and DeFord, 1950; Walter, 1953). These fossils include such distinctive Paleozoic forms as *Derbya sulcata*, *Dictyoctostus* sp., *Marginifera* sp., *Hustedia* cf. *H. meekana*, *Wellerella elegans*, and chonetids.

The age relation of the Ochoan deposits to the Capitan limestone was not understood until the latter was recognized as a great reef deposit and its correlation with the Bell Canyon sandstone of the basin was established. Since then the Ochoan has been generally recognized as younger than the Guadalupian. However, Philip King observes (Personal communication) that

> "C. L. Jones of the U. S. Geological Survey has found subsurface evidence that the highest part of the back reef facies grades laterally into Castile anhydrite. This involves only the upper part of the Tansill—not a large part of the Guadalupian as George Moore (1959) and various predecessors have claimed. The intertonguing thus does not invalidate the gross separation of the Guadalupian and Ochoan series, but it raises problems as to the precise definition of the boundary. Sedimentation in the one series evolved into sedimentation in the other."

It now seems evident that marine faunas younger than Gaudalupian are present in the highest part of the Upper *Productus* limestone (Chideru formation) of the Salt Range in Pakistan and in the Foldvik Creek formation of Central East Greenland. Both are distinguished by the presence of the ammonite genus *Cyclolobus* which Miller and Furnish have shown to be a descendant of *Waagenoceras*. *Waagenoceras* characterizes the Guadalupian, and in the Salt Range underlies the zone of *Cyclolobus*. In both the Salt Range and in East Greenland the basal Triassic (zone of *Otoceras*) rests with apparent conformity on the zone of *Cyclolobus*. Schindewolf (1954), who has recently restudied the upper part of the Salt Range section, believes there was no hiatus here between Permian and Triassic deposition, and Trümpy (1960) believes that some of the brachiopods and bryozoans of the Foldvik Creek beds persisted into

the lower 30 m of the *Otoceras* zone of the Triassic of Central East Greenland. The present writer must express scepticism of unbroken deposition at the Permian–Triassic boundary in either region even though he is persuaded that the zone of *Cyclolobus* is the youngest marine Permian we know. Schindewolf shows that not a single species crosses the Permian–Triassic boundary in the Salt Range and states that among the world faunas only four genera cross the boundary. To explain the sudden and world-wide extinction of the Permian marine faunas before Triassic time he invokes a sudden change in the amount of cosmic rays, which killed off Permian forms and led to rapid evolution of new faunas. The present writer thinks such a reversion to catastrophism is unnecessary and that there is probably a hiatus of considerable magnitude. The alleged carryover of Permian forms into the base of the Triassic in East Greenland also needs more critical field study. Trümpy records this mingling of faunas in a small area about Cape Stosch, and in this area undoubted Permian faunas occur in "white blocks" in limestone conglomerates interbedded at five distinct horizons in the lower part of the Triassic. The beds near the top of the Permian sequence at Cape Stosch yield free fossils, and very critical and detailed field study of the Permian fossils in the basal shale of the Triassic is needed to determine whether they also may have been redeposited.

Granted that the Chideru beds and the Foldvik Creek formation, and possibly the upper part of the section at Djulfa in Armenia (Stoyanow, 1909), are post-Guadalupian, the exact position of the top of the Guadalupian Series in these remote areas is still uncertain. Future faunal studies will probably clarify the relations. Unfortunately no fusulines are known in either of the high Permian formations mentioned above. The zone of *Yabeina* so widespread in the Orient is probably post-Guadalupian, or largely so, but unfortunately the beds carrying *Yabeina* have not yet yielded *Cyclolobus*. We may note, however, the recent discovery (Skinner and Wilde, 1955) of a small and rather primitive species of *Yabeina*, *Y. texana*, in the Lamar limestone near the top of the Guadalupian in the Guadalupe Mountains.

San Andres Limestone

One of the most difficult and controversial problems concerns the age of the San Andres limestone of New Mexico and its correlation with the formations that crop out in central Texas and Oklahoma.

This limestone was named by Lee (1909) for exposures in the northern part of the San Andres Range in south-central New Mexico. It is typically developed also in the Sacramento Range where it is readily recognized by its lithologic characteristics and by its association with the underlying Glorieta sandstone and the Yeso formation. In these ranges where its summit is an erosion surface, the San Andres is only about 500 feet thick. Here it contains brachiopods, among which the large productid, *Dictyoclostus bassi*, is conspicuous. No fusulines are known here, and ammonites are rare. Beede reported a single specimen of a *Perrinites* near Cloudcroft in the Sacramento Range, and Clifton (1946, p. 556) later collected there a fauna of six species of ammonites, including *Perrinites hilli*. Kottlowski (1956, p. 61) also identified *Perrinites* and *Pseudogastrioceras* from the upper part of the formation in the northern part of the San Andres Range, and Miller and Furnish (1957, p. 1053) identified *Perrinites hilli* and *Pseudogastrioceras* cf. *P. serratum* from a collection made by Boyd from near the base of the formation (Cutoff shale equivalent) in the northwest flank of the Guadalupe Mountains.

Since *Perrinites* is very characteristic of the Leonardian and *Dictyoclostus bassi* is abundant in that series but rare or doubtfully present in the overlying Word formation, R. E. King in 1930 correlated the San Andres limestone with the Leonardian, and for a number of years it was generally believed to correlate with the Bone Spring limestone of the Guadalupe Mountains and the Leonardian of the Glass Mountains.

However, as drilling proceeded eastward across the platform north of the Delaware Basin and across the Central Basin Platform into the Midland Basin, the San Andres (then including the overlying Grayburg limestone) was identified as a persistent calcareous unit from which fusulines of Cherry Canyon age were secured from a number of wells. Thus a number, but not all, of the oil-field geologists came to regard the San Andres as equivalent to the Word formation. The evidence for this view has been summarized by Lewis (1941) and by Clifton (1945; 1946).

Skinner (1946) traced the San Andres limestone in continuous outcrop from near Piñon in the east flank of the Sacramento Range southeastward to Dog Canyon in the northwest flank of the Gaudalupe Mountains where he found it

to grade laterally into the lower tongue of the Cherry Canyon sandstone. Here fusulines were abundant in the lower cherty member but have been reduced to hollow molds except in cherty nodules from which Skinner (1946, p. 1865) identified such characteristic Word species as *Parafusulina rothi*, *P. deliciasensis*, *P. lineata*, and *P. sellardsi*. The relations here were later clarified by the work of Newell *et al.* (1955), Boyd (1959), and Hayes (1959). These studies showed that in the Dog Canyon area the upper and major part of the San Andres limestone grades laterally into the lower part of the Cherry Canyon sandstone but that the lower part grades laterally into the Cutoff shale member of the Bone Spring formation. It thus straddles the boundary line; the lower part is Leonardian, and the upper part early Guadalupian (Word).

The Cutoff shale was separated as a distinct member of the Bone Spring formation by Philip King (1942). At its type locality in the west face of Cutoff Mountain, just north of the Texas–New Mexico boundary, this member is about 230 feet thick. It wedges out southward near Shirttail Canyon where it is unconformably overlapped by the feathered edge of the Brushy Canyon sandstone. Boyd traced the Cutoff shale northward into the upper reaches of West Dog Canyon and found it to grade laterally through a transition zone about 2 miles wide into the lower part of the San Andres limestone. At about the same latitude the lower tongue of the Cherry Canyon sandstone similarly grades into the upper part of the San Andres (Fig. 2). Boyd also indicated that, to the northwest, the upper part of the Victorio Peak member of the Bone Spring limestone likewise grades into the basal part of the San Andres. Obviously there is a considerable hiatus between the Bone Spring limestone and the overlapping Guadalupian sandstones on the Bone Spring flexure, but no hiatus has been detected within the San Andres limestone over the shelf area in New Mexico.

Within the Midland Basin the thick limestone unit which Lewis and others identified as San Andres grades laterally into detrital rocks and loses its distinctive character; by following certain conglomerate and sandstone units, however, Lewis (1941) attempted to carry its equivalents eastward to the outcrops in central Texas where he correlated it with the El Reno group. This correlation soon was accepted by other petroleum geologists (Clifton, 1942).

This correlation introduced a further problem, however, which is still unresolved. No fusulines have been found in the outcropping El Reno formations, but ammonites are locally abundant in thin dolostone beds in the Blaine and the Dog Creek shales. Clifton (1942) cited three localities in the Acme dolostone member in Texas and three localities in Oklahoma and an important locality in the Dog Creek shale at the Falls of Salt Croton Creek in Stonewall County and another near Quanah in Hardeman County. In all these El Reno faunas the dominant ammonite is *Perrinites*. Plummer and Scott (1937) identified two species, *P. gouldi* and *P. hilli*, from these beds, but Miller and Furnish (1940b) restudied these faunas and found that there is but a single species of *Perrinites*; they concluded (p. 148), "The writers' studies have proved that only one recognizable species of *Perrinites*—*P. hilli*—is known to occur in North America."

In the Glass Mountains section *Perrinites* is very characteristic of the Leonardian and is succeeded by *Waagenoceras* which appears near the base of the Word formation and ranges up through the Guadalupian. The two genera never occur together. In 1945 Clifton reported the first and only known occurrence of *Perrinites* in the Word, where he thought it to be associated with *Waagenoceras*. These specimens were found in the very base of the thick Word formation (Word limestone No. 1 of P. B. King) in the Glass Mountains. Miller and Furnish (1947) confirmed the identification of *Perrinites hilli* but found the supposed *Waagenoceras* to be a new species of *Stacheoceras*, *S. normani*, which, while probably ancestral to *Waagenoceras*, has much simpler and more primitive septa. Miller and Furnish therefore maintain that the El Reno group should correlate with the Leonardian rather than with the Word. They write (Personal communication of March 21, 1958), "As you suppose, correlation of the El Reno group with the Word is still irreconcilable as far as ammonites are concerned. Granted that the problem is not as simple as once thought and that *Perrinites hilli* does occur abundantly in Word limestone No. 1, nevertheless the sequence of *Perrinites* to *Waagenoceras* remains firmly established in West Texas and Coahuila; there is no conflict in Asiatic localities where these forms occur."

Here then is an irreconcilable conflict in the paleontological evidence based on fusulines in the limestone unit under the Midland Basin and on ammonites in the outcropping El Reno group. Since the fusulines and ammonites are not in conflict wherever they occur together, it seems possible that subsurface tracing on lithologic features in a region of shifting facies is in error, and that the El Reno should correlate

with the upper part of the Leonardian and not with the Word, as postulated by P. B. King in 1942 (p. 694, 703).

The unit identified as San Andres in the subsurface is more than twice as thick as the exposed

who recognized three stratigraphic units: (1) a nonmarine unit at the base followed by (2) a lower marine group and (3) an upper marine group. Both marine groups bear fusulines, and Grönwall's collections are now being studied b

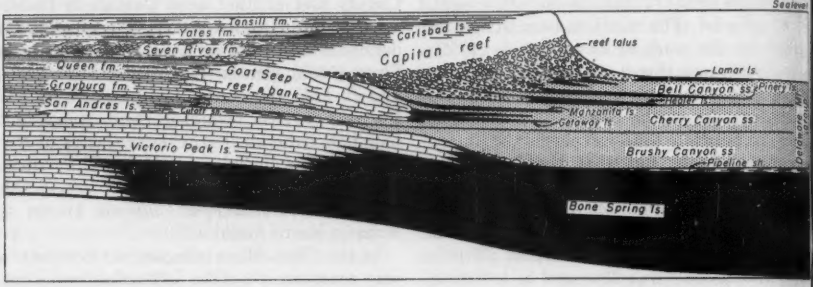

FIGURE 2.—DIAGRAMMATIC SECTION OF THE CAPITAN REEF COMPLEX
Adapted from diagrams by P. B. King (1948) and Newell (1953)

San Andres of New Mexico, and since it now seems evident that the latter includes both upper Leonard and Word equivalents, the thick sections underground probably do likewise and the lower part only has been traced into the El Reno group.

ANNOTATIONS

1. The stratigraphy of the Foldvik Creek formation was summarized by Maync (1942) and reviewed by Dunbar (1955) in a monographic study of its brachiopod faunas. The pelecypods were described by Newell (1955). The brachiopods and pelecypods, like the fishes (Aldinger, 1935; 1937), clearly indicate correlation with the Magnesian limestone of England and the Zechstein of Germany with which they had direct faunal connection. In the United States the closest similarities appear to be with the Phosphoria formation which is not younger than the Guadalupian. On the contrary, Miller and Furnish (1940a) believe the Greenland faunas are of latest Permian age because of the presence of two species of *Cyclolobus* which, in the Salt Range of Pakistan, succeeds the zone of *Waagenoceras*; they would therefore correlate the Foldvik Creek formation with the Ochoan Series. The ammonites are so associated with the brachiopods and pelecypods as to prove that they are all of one faunal zone (Dunbar, 1955, p. 52).

2. The late Paleozoic strata of northeast Greenland were described by Grönwall (1917)

Dunbar, Ross, Norford, and Troelsen who fi that the lower marine group is of Desmoinesia age and the upper marine group is of Wol campian age, bearing species of *Schwagerin* and *Pseudoschwagerina*.

3. The Permian rocks of Ellesmere Islan were briefly described by Troelsen (1950). He he found Lower Permian (Wolfcampian) bed some 700 meters thick resting disconformabl on beds of Moscovian age.

4. A large area of Permian rocks abou Tikchik Lakes, west of the Nushagak Valley i southwestern Alaska was studied by Mert (1938). Here he described an unnamed forma tion estimated to be from 500 to possibly 100 feet thick. J. M. Hoare (personal communica tion) reports that

> "the rocks known to be of Permian age consist fine-grained gray or buff limestone which grad upward into mafic volcanic rocks. The limestone generally at least 50 feet thick. In some places appears to be 400–700 feet thick. Locally the lim stone appears to grade laterally into calcareo conglomerate and sandstone. There is no assuran that the numerous exposures of Permian limest are parts of the same stratigraphic horizon. T overlying volcanic rocks, widely altered to gree stone, consist of massive flows, breccia, and pill lavas. Mertie (1938) estimated the greenstone to 4,500 feet thick on Tikchik Lakes. I do not think is nearly this thick on the Tikchik Lakes, and e where I know it is less than 1000 feet thick."

Mertie (1938) concluded that the greensto is probably a correlative of the Nikolai gree stone of the Tanana region which is on strike

east-central Alaska (column 8). Fossils from the Permian limestone were identified by Girty from two localities (Mertie, 1938, p. 44). Fossiliferous rocks of Permian age also crop out farther north on the north bank of Kuskokwin River west of Aniak (Maddren, *in* Smith, 1939).

5. The Siksikpuk formation, about 350 feet thick, was described by Patton (1957) along the north flank of the central part of the Brooks Range in northern Alaska. Its fauna is undescribed, but preliminary examination of the corals led Helen Duncan to suggest probable Artinskian (Leonardian) age.

Another unnamed formation containing Permian fossils occurs in the western part of the southern foothills section of the north slope of the Brooks Range (Tailleur, Sable, and Dutro, 1958). It contains Mississippian fossils in the lower part and Permian in the upper part; the lower boundary of the Permian is undetermined. Here lithologic types peculiar to the Siksikpuk formation are present in a member more than 4000 feet below the top of the Permian (Tailleur, personal communication).

6. Permian rocks were mapped by Leffingwell in the Canning River area in extreme northeastern Alaska and were named the Sadlerochit formation (Leffingwell, 1919, p. 113–115). These rocks are chiefly thick-bedded light-gray sandstones resting with apparent conformity on the Lisburne limestone (Mississippian). Fossils are not abundant and were chiefly found in the lower part. Girty (*in* Leffingwell, 1919) considered the age to be Pennsylvanian, but the fossils he identified clearly indicate that this is a part of the widespread Permian of Alaska. The Permian age was recognized by Girty (*in* Smith, 1939, p. 32) and later by Gryc (1951). Detailed correlation is, however, still uncertain.

7. Permian rocks are known at several localities along or contiguous to the Upper Yukon Valley where it crosses the Canadian-Alaskan border and is joined by the Nation River. These were named the Tahkandit formation by Mertie (1930) who measured a section of 527 feet of beds of which more than half is limestone. Contrary to the conditions farther south, the Permian rocks in this latitude do not include volcanics. This area was mapped and studied again by Mertie (1937) who reported that the limestones are richly fossiliferous and listed 58 genera and 135 species as determined by Girty. As in other Alaskan Permian areas the faunal affinities are with Russia, and correlations by Girty were tentative.

8. Extensive outcrops of Permian rocks occur along the southern flank of the Alaska Range from south of Mt. McKinley (Long. 150° W.) southeastward to the Canadian border and beyond it. In this region the Permian is thick and includes immense amounts of volcanic rocks as well as thick units of marine sedimentary deposits, including richly fossiliferous limestones. The outcrops occur at a number of isolated localities, and changes of facies are so great that correlation from one area to another has not been possible at the present stage of reconnaissance study so that it is impossible to give a satisfactory generalized section for the whole area.

Capps (1916) made a pioneer study of these deposits in the headwaters of Chisana and White River valleys, near the Canadian border. Mendenhall (1905) studied a fine section about 6700 feet thick in the slopes north of Mankomen Lake (Long. 144° 30′ W.) from which he secured abundant fossils. This is the type section of his Mankomen formation. Unfortunately it is a rather isolated outcrop area and has fewer volcanic rocks than the thicker sections farther east. Its limits in terms of the latter have not been satisfactorily worked out. Moffit (1933) described the section in the Suslota Pass area where volcanic tuffs and lava flows predominate but are interbedded with marine limestone. In 1938 Moffit synthesized the work of Capps and of later Survey parties through 1932 and presented a geologic map of the area. Rohn (1900) had previously introduced the name Nikolai greenstone for a thick sequence of ancient basic volcanic rocks underlying the Chitistone limestone (Upper Triassic) in the Skolai region. Although in many subsequent reports it included much older volcanic rocks the Nikolai greenstone is now restricted to Permian (and possibly Triassic) volcanics of this region. Although its lower boundary seems not to have been clearly defined it apparently is restricted to the volcanic rocks that succeed the marine Permian.

In 1954 Moffit presented a more detailed geologic map of the area from Chistochina River (Long. 145° W.) to the Canadian border and reviewed all the previous work that had been done in the eastern part of the Alaska Range.

Extensive collections of fossils from the limestones in this region were identified for various Survey parties by Girty who recognized their Permian age but, because their affinities are with the Russian province and only very preliminary identifications were made, the position of these beds in the Permian System remains highly problematical.

Along the strike of the rocks above discussed,

but more than 100 miles farther west, Ross (1933) described a sequence of 3500 to perhaps 6000 feet of Permian beds similar to these, consisting of volcanic tuffs interfingering with chloritic argillites, volcanic flows, limestone, and chert. Permian fossils were collected from the limestone at one locality and were identified by Girty.

9. Buddington and Chapin (1929) mapped numerous outcrops of Permian rocks on Skagway and Cornwallis peninsulas and adjacent islands—Admiralty, Kuiu, Keku, and Kupreanof—of southeastern Alaska and recognized two unnamed divisions, the lower probably Sakmarian (Wolfcampian) and the upper Artinskian (Leonardian). The faunas have not been critically studied but are of Russian affinities. From the beds on Kuiu Island Dunbar (1946) described *Parafusulina alaskensis*, believed to indicate Leonardian age.

Outcrops about William Henry Bay on Admiralty Island were studied by U. S. Geological Survey parties in 1956 through 1958 (Lathram *et al.*, 1959). Here a thick sequence of graywacke, greenschist, and phyllite, with some marble, bears fossils in its middle portion, including the Permian brachiopod *Muirwoodia* (Cooper *in* Lathram *et al.*, 1959). This is succeeded by at least 2000 feet of greenschist and amphibolite representing a metamorphosed volcanic section considered to be at least in part Triassic in age (Lathram *et al.*, 1959).

10, 11. The Cache Creek group is a catchall for the late Paleozoic strata of British Columbia and Yukon Territory. It is locally very thick and probably includes numerous unnamed formations and local and even regional hiatuses. In the Lake Penchi area Dunbar has identified Wolfcampian, middle Permian, and late Permian fusulines. Thompson *et al.* (1950) have described both middle and high Permian fusulines from Marble Canyon in British Columbia.

The Asitka group was defined by Lord (1948) in the front ranges of the mountains west of the headwaters of Peace River. It includes a thick sequence of volcanic rocks with interbedded sedimentary deposits. Fusulines examined by Dunbar indicate Wolfcampian age for several of the collections (Lord, 1948, p. 11 and 12) but some of the collections suggest pre-Permian age. Lord concludes, "It is, therefore, thought best to designate the age of the Asitka group as Lower Permian and (?) earlier."

12. Permian beds in Washington are placed according to fusulinid evidence (Thompson and Wheeler, 1942; Thompson *et al.*, 1950; Danner, personal communication).

W. R. Danner writes,

"The Middle and Upper Permian of western Washington contains two fusulinid zones: the *Yabeina* zone and the Verbeekina-Neoschwagerina zone.

"The Lower Permian beds consist mainly of limestone and certain fusulinids and bryozoans. *Schwagerina* is abundant in these beds at both the northwestern Whatcom County locality and the San Juan Island locality which is near East Sound on Orcas Island.

"Nowhere have I found a continuous section with all of the Permian represented, and my thought is that the Middle Permian is largely missing in western Washington, but the missing interval may be represented in eastern Washington by the beds containing *Parafusulina*."

13. The Clover Creek greenstone was named by Gilluly (1937) who reported brachiopods of Permian age in interbedded lenses of limestone. The position of these rocks, within the Permian, and their stratigraphic range are still very uncertain. The Elk Ridge argillite, previously thought to be Precambrian, has been shown by Taubeneck (1955) to be of Leonardian age.

14. The Coyote Butte formation was described by Merriam and Berthiaume (1943), who cite evidence for its age from both fusulines and brachiopods. Cooper (1957) made a critical study of the brachiopods and tentatively assigned the faunas to the lower Guadalupian (lower Word). The affinities appear to be with Russian faunas, however, and the evidence for close correlation with the American standard section is tenuous. In correlating with the Word formation, Cooper apparently places chief reliance on the genus *Muirwoodia*, which in West Texas does not occur below that horizon. The genus has a long range elsewhere, however; the generotype, *M. mammatus* occurs in the lower Permian (Sakmarian) of the U.S.S.R., whereas *M. greenlandica* occurs high in the Permian of Greenland, and *M. multistriata* of the Phosphoria formation may belong as high as Capitan. Most of Cooper's comparisons (Cooper, 1957, p. 14–17) are with species of Sakmarian or Artinskian age, and this age seems to be indicated by the fusulines. L. G. Henbest, who reported on the fusulines for Merriam and Berthiaume, observes (Personal communication),

"Six collections were obtained from the disconnected exposures of the complexly deformed Coyote Butte formation and from boulders of upper Paleozoic limestones in supposed Triassic rocks. The stratigraphic sequence is problematic.

"One collection contains *Parafusulina* (?) *gracilis* (Meek) alone. The other five differ in foraminiferal content and biological facies, but have species in common and appear to belong to a connected sequence having a duration no longer than a single epoch. In these five collections the following significant species were recognized: *Pseudofusulinella occidentalis, P. montis, Schwagerina hawkinsi, Schwagerina* aff. *S. nelsoni, Parafusulina diabloensis, P. imlayi, P. turgida,* and *P.* (?) *calx*. Except for the collection composed entirely of *Parafusulina* (?) *gracilis*, which may be of very latest Wolfcamp age, the nearest relatives of the species of fusulines in Oregon are in the Bone Spring formation and the upper part of the Hueco limestone in the Franklin Mountains. No species of Word or Nosoni foraminifera were recognized. I find no evidence for anything younger than Bone Spring (Leonardian)."

15. The Seven Devils volcanics were described by Lindgren (1900) and redescribed by Anderson (1930) who reported a "Phosphoria fauna" in interbedded calcareous tuffs.

16. The Casto volcanics were described by Ross (1927). No fossils were discovered, but this appears to be an extension of the volcanic field represented in the Seven Devils area to the west.

17. The McCloud formation and the Nosoni formation are both dated by fusulines (Thompson *et al.*, 1946).

The upward range of the Dekkas andesite is problematical. Albers and Robertson (1952) report two zones of well-preserved Permian fossils in sediments interbedded with the Dekkas volcanics. They report also that mapping indicates a hiatus between the lavas and the overlying Triassic.

L. G. Henbest (personal communication) reports the following:

"The Permian age of at least the lower part of the Dekkas andesite in Shasta County, California, is indicated by a collection of fusulinids made by J. P. Albers from 1200 feet above the base of the andesite, near the center of Sec. 8, T.34N, R3W (USGS, F-9010B). *Parafusulina antimonioensis* and *P.* aff. *P. rothi* are present in abundance. Word age and a continuation upward of the Nosoni faunas is indicated."

18. The Keeler Canyon formation (Merriam and Hall, 1957, p. 4–7) is dated by fusulines and brachiopods. The lower two-thirds is Pennsylvanian, but the upper part, with *Schwagerina* and *Tricities*, is basal Wolfcampian.

The Owens Valley formation (Merriam and Hall, 1957, p. 7–12) includes three faunal zones. The lower 1000 feet includes *Schwagerina, Pseudoschwagerina, Paraschwagerina, Parafusulina* (?), *Triticites, Heritschia,* and *Omphalotrochus* and is clearly Wolfcampian. The middle zone, 400–700 feet thick, has yielded *Schwagerina, Parafusulina, Heritschia,* and *Parenteletes* and is probably Leonardian. The upper zone, 180–500 feet thick, is characterized by *Spiriferina pulchra* and *Neospirifer pseudocameratus* and clearly correlates with the Phosphoria formation.

An angular unconformity separates the Keeler Canyon formation from the Owens Valley formation on the west side of the Inyo Range but is not recognized in the Darwin quadrangle.

19. The Anvil Spring formation (Johnson, 1957, p. 382–384), about 4000 feet thick, is lithologically somewhat like the Bird Spring formation of Nevada. Fusulines indicate that the lower part is Pennsylvanian and the upper part Wolfcampian (unpublished data by Wrucke). It is overlain by Triassic volcanics of great thickness.

20 and 21. In these areas the Kaibab (Kaibab and Toroweap not separated) can be recognized by its lithologic characteristics and fauna, and its stratigraphic position. The underlying redbeds are of Hermit facies, but they occupy the stratigraphic position of the Coconino sandstone and the Hermit shale of sections farther east. The Bird Spring limestone has been dated by abundant fusulines (Longwell and Dunbar, 1936; Thompson *et al.*, 1946); the lower part is Pennsylvanian, and the upper part Wolfcampian, possibly extending into the basal part of the Leonardian. In this area a great hiatus separates the Kaibab from the overlying Moenkopi (Triassic) formation.

22. The Koipato group was originally considered to be Triassic and to include about 6000 feet of beds, chiefly argillite (Hague, 1878). Ransome (1909, p. 32–33) showed that these are chiefly metamorphosed volcanic rocks. This was confirmed by Knopf (1924) who named and described the Rochester trachyte, the Nenzel breccia, and the Weaver rhyolite. The Limerick keratophyre was named by Jenny (1935).

The stratigraphic range of this volcanic complex remains highly problematic. Probably volcanic activity in the region was more or less continuous from somewhere in the middle Permian to early Triassic time.

The unnamed limestone formation near Quinn River bears fusulines of Wolfcampian and lower Leonardian age and is possibly an extention eastward of the McCloud formation of California (Siemon Muller, personal communication).

23. The Diablo formation contains, near its base, "a fauna characteristic of the Phosphoria formation" (Ferguson and Cathcart, 1954).

The range of the Pablo formation, like the Koipato, is highly problematical. It may or may not range up into early Triassic. In the Shoshone Mountains it is overlain by the Middle Triassic, Grantsville, formation (Silberling, Personal communication).

24 and 25. For a recent synthesis of the complex geology of this part of Nevada *see* Roberts *et al.*, 1958. The Antler Peak limestone is an autochthonous facies, but the Havallah formation is a detrital facies thrust over this area from the west. Outcrops are scattered and discontinuous.

The best evidence of dating is from fusulines studied by Henbest and Douglass who find that the Antler Peak limestone ranges from Late Pennsylvanian to Early Permian. The Havallah formation bears early Middle Pennsylvanian (Atokan) fusulines in its lower member and Wolfcampian fusulines in its upper member, culminating in a faunal zone believed to be early Leonardian.

The Edna Mountain formation was correlated by James Steele Willians with the Gerster formation of the Phosphoria complex (Roberts *et al.*, 1958; Muller *et al.*, 1951).

26. The Carbon Ridge formation is dated chiefly by fusulines studied by Henbest. The lower zones, containing *Pseudoschwagerina* and *Schwagerina*, are clearly of Wolfcampian age, but the highest zone, with *Parafusulina gümbeli* (?), should be lower Leonardian (Nolan *et al.*, 1956, p. 65–66).

The Garden Valley formation, separated in outcrop from the Carbon Ridge formation, has yielded fusulines of Wolfcampian age in its lower part. This formation is believed to be approximately equivalent in age to the Carbon Ridge formation, from which it differs lithologically in being largely detrital (Nolan *et al.*, 1956).

27. Dott (1955, p. 2219, 2248–2255) defined the Strathearn formation and showed that the lower part is Pennsylvanian and the upper part Wolfcampian. An overlying, unnamed unit also yielded *Schwagerina* of Wolfcampian type.

28. This extremely important key section in the Confusion Range of central western Utah was worked out by Richard Hose and Charles Repenning who have just finished a critical restudy of the area (Hose and Repenning, 1959).

The type section of the Arcturus limestone is in the Ely district where it was described as a "shaly limestone". Equivalent beds in the Elko area are more detrital and are termed the Arcturus formation. About Elko the formation is sparsely fossiliferous and not well dated except for its position between the Ely limestone and the Kaibab. In the White Pine district northwest of Ely, it bears abundant fusulines which Knight (1956) believes to have a range from upper Wolfcampian to middle Leonardian.

The Ely limestone, named and studied in the Ely district, is dated by fusulines (Hose and Repenning, 1959, p. 2174); the lower part is Pennsylvanian, and the upper part Wolfcampian.

The Kaibab limestone is identified both lithologically and faunally and is considered approximately equivalent to the Kaibab in the Grand Canyon, although it possibly ranges somewhat higher.

The Plympton formation is a sequence of dolostone, siltstone, and chert, with some black phosphatic shale. It resembles lithologically the Meade Peak tongue of the Phosphoria and Park City complex but it has yielded very few fossils.

The Gerster formation appears to be a westward extension of the upper part of the Franson member of the Park City formation and has yielded abundant brachiopods which Gordon regards as upper Guadalupian (Capitan) (C. A. Repenning, personal communication).

29–35. These columns were arranged by V. E. McKelvey, and supporting data for the Park City-Phosphoria complex has been published by McKelvey *et al.* (1956) and McKelvey *et al.* (1959).

The Oquirrh formation has been dated by fusulines (Bissell, 1950, p. 891; Thompson, 1954, p. 27–29); the lower part is Pennsylvanian, but the upper 9000 feet is Wolfcampian.

Referring to Column 29, A. A. Baker writes

"It is unfortunate in some respects to try to give one consolidated section under this heading, linking the two facies that exist on the two sides of the zone of the thrusting. In the range north of the thrust the Park City formation of McKelvey *et al.* rests on the Weber quartzite of Pennsylvanian age with no intervening units, whereas in the Hobble Creek area south of the fault a greatly thickened section of the Park City formation (in which I have recognized only the upper and lower members separated by the middle phosphatic shale member) rests on the Diamond Creek sandstone which in turn rests on the Kirkman limestone. The Diamond Creek presumably is continuous with the Coconino sandstone. The Kirkman rests on the Oquirrh which contains fusulines of Wolfcampian age in the upper part according to Henbest's identification."

The upper limit of the Wells formation is uncertain; McKelvey *et al.* suggest that it continues without important break to the base of

the Park City formation, but H. D. Thomas thinks it includes only part of the Wolfcampian as represented in columns 31 and 32.

Although some writers recognize the Owl Canyon formation in the area of the Hartville Uplift, H. D. Thomas advises that the Wyoming Geological Survey uses the term Cassa group for all the beds in this area between the Broom Creek group and the Opeche shale.

36. This and the following three sections are based largely on data from Thomas (1934), Burk and Thomas (1956), and Condra *et al.* (1950), but correlation of units of the Goose Egg formation is keyed to the preceding columns, since the Minnekahta, Forelle, and Ervay limestones are tongues of the Phosphoria complex extended eastward into the redbeds. The Opeche, Glendo, and Freezeout are unfossiliferous units, mainly red shales. The lower limit of the Opeche, in terms of standard time, is uncertain.

Verville (1957) described lower Wolfcampian fusulines from the upper part of the Tensleep sandstone in the Bighorn Mountains area, but at most places the top of the Tensleep is no younger than Pennsylvanian.

37. In the northern part of the Laramie Basin the Goose Egg formation can be recognized in its entirety, but to the south all limestones except the Forelle thin out, and the Opeche and Glendo together form an unfossiliferous red shale called the Satanka. Permian redbeds above the Forelle are included in the base of the Chugwater formation. It is possible that the Satanka of the southern part of the Laramie Basin contains in its lower part redbeds which are equivalent to the Owl Canyon formation of north-central Colorado. (*See* Column 43.)

Thompson and Thomas (1953) described lower Wolfcampian fusulines from the upper part of the Casper formation from localities along the Laramie Range, and Pederson (1954) described a brachiopod fauna of the same age from the upper part of the Casper formation near Laramie. The lower part of the Casper, however, carries Middle and Late Pennsylvanian fusulines.

38. Condra and Reed (1935) separated the uppermost beds of the Hartville formation, designated them as "Division I", and questionably classed them as Permian, since no diagnostic fossils were found. Later, Condra *et al.* (1940) divided "Division I" into the Broom Creek and Cassa "groups". Other workers (*e.g.* Bates, 1955) have correlated the upper part of the Hartville limestone with the Wolfcampian part of the Casper formation. Edwin K. Maughan (Personal communication, 1960) believes the Broom Creek to be the exact equivalent of the Ingleside formation of north-central Colorado (*see* Column 43), in which Wolfcampian fusulines have recently been found. The time span of the Cassa "group" is uncertain, but if its upper sandstone correlates with the Lyons sandstone of north-central Colorado, as Condra *et al.* believed, its upper part may be as young as Leonardian.

39. Of the limestone tongues in the Goose Egg formation in Wyoming, only the Minnekahta limestone reaches into the rim of the Black Hills, where it separates the distinctive purplish-red shale of the Opeche from the overlying Spearfish redbeds. The upper limit of the Permian in the Spearfish redbeds is problematical.

Because of regional relations, a number of workers (*e.g.* Bates, 1955) have thought that the upper part of the Minnelusa formation is coextensive with the Wolfcampian parts of the Casper and Hartville formations. Recently, Jennings (1959) reported fusulines from the Minnelusa which were identified as of late Virgilian or early Wolfcampian age; he says that faunal evidence "strongly suggests that the bulk of the Minnelusa Formation in the northern Black Hills in Permian in age". In cores from a deep well drilled west of the Hills, fusulines dated by M. L. Thompson as Missourian in age occur only a few feet below the base of the Opeche shale (Horace D. Thomas, personal communication, 1960), suggesting that an unconformity of considerable magnitude separates the Opeche from the underlying Minnelusa.

40 and 41. These columns are based largely on the work of Brill (1952), and they present insoluble difficulties. The Maroon formation consists of unfossiliferous redbeds and is no more than a facies, ranging widely in age and in stratigraphic position and varying in thickness from place to place. In places it is probably as old as Pennsylvanian and in others it ranges into the upper part of the Permian. Hiatuses are difficult to locate and to evaluate.

In the Cottonwood Springs area the thin South Canyon Creek dolostone appears to be a tongue of some part of the Park City–Phosphoria complex, and Bass and Northrop (1950) reported on a considerable molluscar fauna.

Brill (1952) named the State Bridge formation in the McCoy area. The lower part is believed to be a Phosphoria equivalent, and the upper part Triassic (Trask, 1956; Hebrew and Picard, 1955).

The Weber sandstone, like the Maroon for-

mation, is a facies differing greatly in age from one area to another and is generally unfossiliferous. In places its lower portion is as old as Desmoinesian (Langenheim, 1954).

42. The Sangre de Cristo formation, as much as 9000 feet thick in the Whiskey Pass area, is only indirectly dated. Traced southward into New Mexico it underlies Leonardian equivalents and probably grades laterally into the Abo formation. Near the Arkansas River it has yielded vertebrate fossils that occur also in Wolfcampian beds in Kansas, Oklahoma, and Texas. In southern Colorado it rests disconformably on mid-Pennsylvanian (Desmoinesian) strata (Brill, 1952).

43. The Ingleside formation, long classed as Pennsylvanian, is now known to be of Permian age through the recent discovery of a single but excellently preserved specimen of a Wolfcampian fusuline which was found in its basal bed (Edwin K. Maughan, personal communication, 1960). The time span of the overlying unfossiliferous Owl Canyon formation is problematical. The Lyons sandstone has not yielded invertebrate fossils but is classed as Leonardian on the basis of regional subsurface correlation with the Kansas section (Maher and Collins, 1952). It has been studied regionally by W. O. Thompson (1949) who found vertebrate tracks, some of which seem to be identical with forms found in the Coconino sandstone.

There has been some disagreement as to which of the limestones in the Goose Egg formation of Wyoming are represented by the "crinkly limes" along the Front Range, but most workers have correlated the lower one with the Minnekahta and the upper one with the Forelle. The upper "crinkly lime" is overlain by the unfossiliferous Lykins redbeds, which in the original sense extended down to the top of the Lyons sandstone. The upper limit of the Permian in the Lykins is problematical.

44. *See* comments for Columns 36–39. In the subsurface of southeastern Colorado, Maher and Collins (1952) recognize the upper part of the Fountain formation as extending up to the base of the Lyons sandstone.

The Lykins consists of generally unfossiliferous redbeds and is probably continuous with the Spearfish shales of the Black Hills region. In the Golden area the Permian part of the Lykins shale was subdivided into five members by Le Roy (1946) who correlated the Falcon and Glennon limestones with the Minnekahta and Forelle limestones, respectively, of Wyoming.

45. In this area McNair (1951) named the Pakoon formation and showed that it bears the *Pseudoschwagerina* fauna of the Wolfcampian. Maughan notes (Personal communication),

> "This rock is similar lithologically and almost certainly continuous with the Wolfcampian part of the Callville and Bird Spring formations [Columns 20 and 21] farther west, and it can be shown, by tracing, to be equivalent to the Carbonate rocks near the base of the Supai formation (originally classed with the Redwall limestone) eastward through Grand Canyon. The term dolomite is misleading, for the rock unit consists of cyclic deposits very similar to those in the Pennsylvanian (Callville and Bird Spring) below. Although it includes dolostone it also includes beds of limestone and redbeds—typical cyclothems".

McNair (1951) proposed the name Queantoweap for a more sandy facies of the Supai formation in this region and used the name Hermit shale instead of Supai for the finer-grained facies. He considered the Queantoweap sandstone to be an extension of Unit A of Noble's section of the Supai at Bass Trail. E. K. Maughan (Personal communication), who has worked in this area during the past 5 years, thinks the term Queantoweap is superfluous and that the name Supai should be used for all the beds between the Pakoon formation and a westward extension of the typical Hermit shale.

The Coconino, Toroweap, and Kaibab units are readily identifiable, on the basis of lithologic characteristics and stratigraphic position.

46 and 47. These columns represent the classic section of the Permian of the Grand Canyon. The Kaibab limestone of older authors was subdivided into Kaibab limestone (restricted) and Toroweap formation by McKee (1938). Each represents a cycle of deposition, and they are separated by slight local unconformity. The faunas of both were studied by McKee. No fusulines have been found in the Kaibab limestones, and ammonites were virtually unknown until Miller and Furnish in 1958 described several rather well-preserved specimens of a single species of goniatite, *Pseudogastrioceras mckeei*, from a locality near Lees Ferry in northern Arizona. It was described as distinct from, but closely similar to, a species found in the Phosphoria formation. The Kaibab limestone is correlated with the Leonardian chiefly on the basis of brachiopods and because a unit believed to be Kaibab underlies the Phosphoria formation in the Confusion Range (Column 28).

In Column 47 the Toroweap formation is represented mostly by red sandstone, the limestone member having disappeared. E. K. Maughan (Personal communication) notes that

at the mouth of the Little Colorado River the Hermit shale is not more than 100 feet thick, whereas it thickens to 300 feet at Hermit Trail and to 800 feet in the western part of the Grand Canyon.

The Coconino sandstone is the subject of an impressive monograph by McKee (1943). Its only fossils are vertebrate tracks. Toward the east it thickens and replaces the marine limestones above.

The Hermit shale and the Supai formation are redbeds and have yielded only plant fossils in this area. Plant fossils from the Hermit shale were studied by David White (1939) who regarded them as high in the Lower Permian (White was thinking in terms of a two-fold division, Lower and Upper Permian). He also recognized that a few fossil plants found near the base of the Supai (genus *Supaia*, etc.) were also Permian.

In this region, upon the broad Grand Canyon dome, the entire Supai is probably Permian; Pennsylvanian rocks are probably absent. Farther southeast, however, the Supai facies descends in the section, and its basal part has yielded Pennsylvanian fusulines (Jackson, 1951).

48–50. In the Mogollon Rim and in the Ft. Apache Indian Reservation the youngest Permian formation is the Coconino. In the Mogollon Rim the underlying Supai formation was subdivided by Jackson (1951) into four members. An important key unit here is the Apache limestone member which is thin in the Rim but thickens to the southeast to its type section in the Ft. Apache Indian Reservation. It is almost certainly a tongue of the Colina limestone of southeastern Arizona which was dated by Sabins (1957, p. 494) as straddling the Wolfcamp-Leonard boundary. *Omphalotrochus* was found in the lower part in the Tombstone Hills by Gilluly *et al.* (1954, p. 40) and in the Whetstone range by Tyrrell (Unpublished data), and Knight regards this as evidence of Wolfcampian age. On the other hand, in the Dos Cabezas Range Sabins found in its upper part such characteristic Leonardian fossils as *Perrinites hilli*, *Dictyoclostus bassi*, and *Meekella pyramidalis*. The Earp formation of the Tombstone Hills, the Dos Cabezas Range, and the Whetstone Range also includes both Pennsylvanian and Wolfcampian strata as shown by abundant fusulines (Sabins, 1957).

The Scherrer sandstone of southeast Arizona is apparently a continuation of the Coconino sandstone which it resembles lithologically.

The Concha limestone carries a Kaibab fauna in which both *Dictyoclostus bassi* and *D. occidentalis* are conspicuous (Willis Tyrrell, unpublished data).

The Rain Valley formation bears a fauna that has not been critically studied, and it may be uppermost Kaibab but is possibly basal Guadalupian (Bryant, unpublished data).

John W. Skinner (Personal communication) reports that the Horquilla-Earp contact transgresses time upward toward the southeast, and in the Big Hatchet Mountains of New Mexico it is as much as 1000 feet above the base of the Wolfcampian.

51. The fauna of the "Kaibab" limestone in the San Rafael Swell is largely different from that in the typical Kaibab limestone of the Grand Canyon region and includes several forms suggesting relationship to the Phosphoria formation, notably *Waagenoconcha montpelierensis* and *Neospirifer pseudocameratus* (McKee, 1938, p. 175–176). In view of the large covered interval separating these exposures it is uncertain whether the faunal differences are due to facies or whether the limestones in the Swell represent a higher zone of the Kaibab removed by later erosion throughout the Grand Canyon region. Since the Kaibab fauna (with *Dictyoclostus bassi*) is now known to underlie the Phosphoria formation (with *Waagenoconcha montpelierensis* and *Spiriferina pulchra* in central and west-central Utah, Column 28) possibly the "Kaibab" of the San Rafael Swell is a southern tongue of the Phosphoria and is unrelated to the true Kaibab. There may thus be a hiatus in this region between the Coconino sandstone and the "Kaibab" limestone.

The age of the base of the Coconino sandstone in the Swell is also uncertain. Gilluly measured 695 feet of typical Coconino sandstone in Black Box Canyon of San Rafael River underlain by 26 feet of interbedded sandstone and limestone lithologically similar to the Rico formation. Since no fossils were observed in these beds their age is problematical.

52–55. In this region the Permian section is almost entirely nonmarine and generally unfossiliferous. However, A. S. Romer notes (Personal communication) that Camp collected good material at Monument Valley and that good material from the Cutler of Utah and Colorado is now being studied by P. P. Vaughn. It consists of thick masses of gray, commonly cross-bedded dune sand and of red siltstones and shales whose relations are suggested in Figure 1.

In southwestern Colorado two formations are recognized, the Cutler consisting of a thick sequence of unfossiliferous redbeds and the

Rico, a basal unit of redbeds with interbedded marine limestones. These limestones tongue out and disappear in the redbeds, and, where they are missing, equivalent deposits are included in the Cutler. In the Moab and San Juan River areas the Rico limestones carry Wolfcampian fusulines, but farther east, in the San Juan Basin, fusulines of Desmoinesian age have been found in the basal part of the Rico (Henbest, 1948).

56. The thick Permian section about Las Delicias in southern Coahuila ranges through the Leonardian and Guadalupian series. It has not been subdivided into named formations but has been described and its faunas illustrated by R. E. King *et al.* (1944). The faunas are so similar to those of West Texas as to indicate a direct seaway connection.

57. The Monos formation and its faunas have been described by Cooper *et al.* (1953). Correlation with the Word formation of Texas is clearly indicated.

58. In this disturbed region several small areas of Permian outcrop were found by Imlay (1939). Fusulines from three such areas were studied by Dunbar (1939b).

In the Cañon El Tigre near Santa Rosa, Imlay measured a section of 4250 feet of post-Mississippian beds (his units 1, 2, and 3 in descending order). A few fusulines found low in unit 3 were determined by Dunbar to be a small species of *Triticites* indicating probably late Pennsylvanian but possibly early Wolfcampian age. Near the top of unit 3 and in units 2 and 1 the fusulines clearly indicate Leonardian age. The position of the boundary between Leonard and older beds is unknown, but at least 2200 feet of Leonard beds is present.

59. This Permian section near the Guatemalan border in southern Chiapas was described by Mullerried *et al.* (1941), and the ages were determined by rather abundant fusulines (Thompson and Miller, 1944). A remarkable feature of this section was the discovery of the Oriental genus *Eoverbeekina* in the Paseo Hondo formation.

60. According to Wood *et al.* (1946) the Abo formation intergrades with and intertongues with the Madera formation locally and likewise intergrades with and intertongues with the Yeso formation. North of latitude 36° N. both the Abo and Yeso equivalents are classified as Cutler.

Romer (1950) reported on large faunas of primitive vertebrates in the Abo formation of this region, many elements of which occur also in north-central Texas. He states (Personal communication) that the Abo fauna is approximately equivalent in age to the Putnam formation of Texas.

61. Wilpolt *et al.* (1946) separated marine beds at the base of the Abo as the Bursum formation in central New Mexico. It carries fusulines which Thompson (1954, p. 18) identifies as of early Wolfcampian age. This would seem to indicate that in its type region the Abo is all Permian.

The Abo is nonmarine in this region. Plants found in the upper part are believed by C. B. Read to be as young as Leonardian (*fide* Wilpolt *et al.*, 1946).

Furnish writes (March 1, 1960) that the ammonites described by Miller (1932) from the Abo near Tularosa *could be* early Wolfcampian in the light of present knowledge since both *Eoasianites* and *Goniloboceras* are both known to occur in the basal Permian.

George Dixon states (Personal communication)

> "we know of no evidence of an unconformity below the Glorieta sandstone in these areas [Columns 61 and 62]. Charles Read (Personal communication) states that a tongue of Yeso splits the Glorieta in the Manzano-Sandia region, and Needham and Bates say that the Glorieta is conformable on Yeso."

62. Needham and Bates (1943) recognized at the base of the Abo formation an unnamed "basal Permian limestone". This was recognized as the Bursum formation of Wilpolt *et al.* (1946) by them and by Thompson (1954) who reported on fusulines. Thompson (p. 18) notes that some of the upper beds of the underlying Bruton formation also bear basal Wolfcampian fusulines and proposed that that formation be redefined to include only Pennsylvanian strata and that the Wolfcampian beds be shifted to the Bursum formation.

This area includes the type section of the San Andres limestone which is about 300 feet thick. However, its top is eroded so that its original thickness is unknown. It has been traced eastward into the northern part of the Guadalupe region by Skinner (1946).

63. In the Franklin Mountains, north of El Paso, only the Hueco formation of the Permian is preserved. Here it bears abundant fusulines that were described by Dunbar and Skinner (1937).

In its type section in the Hueco Mountains the Hueco formation rests with appreciable angular discordance on Pennsylvanian strata and includes at its base a local limestone conglomerate (Powwow); farther south, in hills

at the south end of the range, it overlaps onto Ordovician rocks (P. B. King, 1934, p. 742). The Hueco formation reaches a thickness of about 1600 feet and forms the surface over a large part of the Diablo Plateau. It is dated by abundant fusulines (Dunbar and Skinner, 1937), by brachiopods (R. E. King, 1930), and by ammonites at two localities. A very early Permian fauna was described by Miller and Furnish (1940b) from near the south end of the Hueco Mountains, and another fauna from the Middle Hueco of Otero County, New Mexico, was described by Miller and Parizek (1948) and determined by them to resemble that in the Wolfcamp formation of Texas and the Admiral and Clyde formations of Texas, and to be Early Permian. (*See* King, King, and Knight, 1945.)

64. Here, as in the Hueco Mountains, the Hueco formation overlaps across Pennsylvanian and older rocks, and toward the south it rests on the Precambrian. Here it is succeeded by the Bone Spring limestone which in Victorio Peak reaches a thickness of about 2000 feet and includes the type section of the Victorio Peak member (P. B. King, 1942, p. 569).

In the Victorio Peak area the Bone Spring limestone rests disconformably on the Hueco formation, but a marked faunal break suggests a hiatus, and in Apache Canyon there is evidence of considerable erosion of the Hueco beds at the contact (King, 1942, p. 629–633).

65–68. This classic area for the Permian of West Texas is the subject of extensive literature most of which is summarized by P. B. King (1948) and by Newell *et al.*, (1953).

The Hueco formation is not exposed in this area but is known from deep wells to be present under the Delaware Basin, in a dark-shale facies.

This is the type region of the Guadalupian Series whose complicated facies relations are indicated in Figure 2. The age and relations of the San Andres limestone are discussed in the Introduction.

The Grayburg and Queen formations have been placed in the upper Guadalupian by some students, but the Shattuck tongue at the top of the Queen sand seems to be a key bed tying the Queen to the top of the Goat Seep reef (Newell *et al.*, 1953, p. 36).

In this region the Brushy Canyon formation and the Cherry Canyon formation and its included limestones are characterized by a coterie of species of the genus *Parafusulina*, whereas the Capitan and Bell Canyon and equivalents are characterized by species of *Polydiexodina* up to and including the McComb member. No large fusulines have been found in the Lamar limestone or its equivalents which on the contrary has yielded a single species of the Oriental genus *Yabeina* and the remarkably specialized small fusuline, *Paradoxiella* (Skinner and Wilde, 1955; Wilde, 1955).

Polydiexodina is clearly a specialized descendant of *Parafusulina*, distinguished by the development of auxiliary tunnels. Why no species of the latter genus survived in this region after the close of Cherry Canyon deposition is an unsolved problem. It is to be expected that in other provinces *Parafusulina* and *Polydiexodina* may be found together in beds of Capitan age or younger. The demise of the large fusulines in this province before deposition of the Lamar limestone may be due to environmental conditions.

The Ochoan Series is discussed in the Introduction.

69. The Glass Mountains reveal a section on the south margin of the Delaware Basin, a counterpart of that in the Guadalupe Mountains. It supplements the latter because the pre-Guadalupian part of the section is well exposed and very fossiliferous. The type sections of the Wolfcampian and Leonardian series have therefore been selected in this area. The Glass Mountains section has been dealt with in the classic studies of P. B. King (1930) and R. E. King (1930). Its brachiopod faunas were described by R. E. King (1930), its ammonite faunas by Böse (1919) and by Miller and Furnish (1940a), and its fusulines by Dunbar and Skinner (1937) and by Ross (1959). A more extensive study of its brachiopod faunas is now in progress by Cooper.

Although the Wolfcampian beds are richly fossiliferous, they now appear to leave much to be desired as a standard for a series. The exposed deposits were laid down along or very near the margin of a basin of deposition bounded by rising highlands on the south. Along the outcrop belt they vary greatly in thickness and show rapid changes of facies. Here their maximum thickness is not more than 600 feet, whereas in the basin north of the Glass Mountains Hall (1956) reported that deep wells have penetrated as much as 9000 feet of beds identified as Wolfcampian. Hall believes that the exposed beds are only the upper part of an onlapping sedimentary sequence. Ross (1959) has subdivided the outcropping sequence into two formations and made a detailed study of facies changes. He has shown that the upper limit should, in places, be drawn somewhat higher than mapped by King. The lower boundary re-

mains somewhat controversial and is now being critically studied in a co-operative project by Cooper, Moyle, Dunbar, and Ross.

The Leonardian Series in the western part of the range represents the basin facies, and the Hess member is a more limy shelf facies.

In this region the Leonardian Series is characterized by the ammonite genus *Perrinites*, and the overlying Guadalupian Series by the genus *Waagenoceras*, and in this region the two genera do not overlap. However, the discovery by Cooper of a species of *Perrinites* in the lower part of the Word formation in its type area (Word limestone No. 1 of P. B. King) was followed by a further study by Clifton who collected *Perrinites* and a supposed *Waagenoceras* along with other ammonites in this limestone (Clifton, 1945). Miller and Furnish later (1957) showed the alleged species of *Waagenoceras* to be a *Stacheoceras* and described it as a new species, *S. normani*. They nevertheless recognize it as an almost ideal precursor of *Waagenoceras dieneri* which characterizes higher zones in the Word.

The Vidrio formation represents a reefy shelf facies of the upper part of the Word formation.

The Altuda formation includes basin deposits correlative with the lower part of the Capitan reef, and the Gilliam is the back-reef facies of its upper part.

The Tessey limestone has only a limited outcrop on the extreme north flank of the range and is not dated by fossils but is believed to represent shelf deposition correlative with part of the thick saline deposits of the Ochoan Series of the basin.

70. The long Permian section of the Shafter District was dated by Skinner (1940), and the names Ross Mine and Mina Grande were proposed by Rix (1953).

71–73. Data for these columns is based on subsurface correlation (R. E. King *et al.*, 1942) and on personal communications from John Skinner.

The Wolfcampian is probably well developed under the Delaware and Midland basins but is much reduced in thickness by overlap onto the Central Basin Platform.

Skinner urges that the name Wichita should be used for the post-Wolfcampian and pre-Clear Fork part of the section. Here beds equivalent to the Belle Plains formation of central Texas carry the *Schwagerina crassitectoria* fauna which should fall near the base of the Leonardian. A. S. Romer (Personal communication) protests this usage as follows:

"The original Wichita was clearly defined as including the beds from what is now called the Pueblo formation up to the Bead Mountain limestone at the top of the Belle Plains. Later, when 'Albany' was abandoned, the Clyde and Lueders were added to the Wichita."

The Brushy Canyon formation is present under the Delaware Basin and the Midland Basin but is absent on the Central Basin Platform as it is on the platform in the Guadalupe Mountains.

Steven Oriel (Personal communication) advises that the complex of sandstone and limestone under the San Andres formation in the Midland basin extends down into Leonardian equivalents and should not be called Brushy Canyon. The precise position of the Spraberry and Dean sandstones in Column 73 is uncertain.

The correlation of the San Andres limestone in this area involves the problems discussed in the Introduction.

74. When the name "Wichita beds" was introduced by Cummins (1890), it was applied to redbeds north of Brazos River and was supposed to be younger than the partly marine beds south of the river to which the name Albany beds was applied and which were considered of Pennsylvanian age but are now known to be a contemporaneous facies. In later years when the base of the Permian was lowered in this region to include the Putnam, Moran, and Pueblo formations, the Wichita group was extended to include these beds. John W. Skinner (Personal communication) recommends that the Wichita should be restricted to the post-Wolfcampian and pre-Clear Fork formations and states that this is the present general usage of petroleum geologists of the region; A. S. Romer (Personal communication) thinks it should include the Wolfcampian equivalents.

Robert Roth (Personal communication) believes that the Permian extends down to the base of the Avis sandstone of the Thrifty formation and that the Belle Plains formation straddles the Wolfcamp–Leonard boundary which is just above its Elm Creek limestone member.

Correlation of the Pueblo to Admiral beds with the Wolfcamp Series is based largely on fusulines. Correlation of the Belle Plains formation with the basal part of the Leonardian is likewise based on the presence of *Schwagerina crassitectoria* (by J. W. Skinner). Wolfcampian ammonites were described from the upper part of the Admiral formation by Plummer and Scott (1937).

Heretofore no fusulines have been reported

1789, column 1, *for* first sentence, lines 14–19, *read*: Robert Roth (Personal communication) believes that the San Angelo formation is approximately equivalent to the Duncan and Cedar Hills sandstones farther east; the San Angelo is transitional to the Flowerpot shales above but is bounded by a hiatus below.

from the outcrop belt above the Admiral formation. Lloyd G. Henbest (Personal communication) has found immature specimens in the Talpa limestone member of Clyde formation in Runnels County suggesting *Schwagerina guembeli* or *S. crassitectoria*, indicating Leonardian age. A short distance down dip, Skinner (Personal communication) has identified *S. crassitectoria* in a zone confidently believed to be in the Belle Plains formation, and on this basis that formation also is correlated with the basal part of the Leonardian Series.

Robert Roth (personal communication) believes that the San Angelo formation is approximately equivalent to the Duncan and Cedar Hills sandstones farther east and that the San Angelo is bounded by hiatuses both above and below. He would place the entire Pease River group opposite the Cherry Canyon formation, leaving a hiatus from here eastward representing the time of deposition of the Brushy Canyon formation.

Ammonites occur locally in the Belle Plains, Clyde, Arroyo, Choza, and Blaine formations (Plummer and Scott, 1937), including the genus *Perrinites*. Plummer and Scott correlated the lower of these ammonites with the Leonardian, but referred those of the Blaine to the Word. However, Miller and Furnish (1940a and personal communication) have long maintained that all the *Perrinites* beds are of Leonardian age. Subsurface correlation across the unexposed area between central and West Texas have persuaded many of the petroleum geologists that the Blaine can be traced into the San Andres which now seems to be in large part lower Guadalupian. The overlying Whitehorse group was referred to the Guadalupian by Newell (1940), who suggested that faunal evidence indicates correlation with the Capitan.

75-77. These columns were arranged by C. C. Branson except that the Quartermaster formation and its equivalents are higher than he indicated. Branson believes there are no major hiatuses in the Oklahoma sections.

78-79. The Nippewalla and Whitehorse groups of Kansas and Nebraska, and their equivalents in Oklahoma, are virtually unfossiliferous. Correlations are therefore based on physical stratigraphy. They are related to the section in central Texas by surface tracing and to the exposures in Colorado and Wyoming by subsurface correlation under the Great Plains. It is impossible to reconcile some of the conflicting opinions, and, although columns 75 to 78 show the classification now used in the areas indicated, the correlation of these formations with those farther west must be considered very tentative.

Until 1954 all of the Sumner and Nippewalla formations were referred to the Leonardian Series (Moore *et al.*, 1951; Maher and Collins, 1952). On the basis of subsurface correlation, however, Maher (1954) concluded that the Blaine of Kansas is equivalent to the "Lower Crinkley limestone" of the Lykins formation in Colorado, which LeRoy (1946) had named the Falcon limestone and had correlated with the Minnekahta limestone of Wyoming. Since the latter is near the base of the Phosphoria complex he raised the upper part of the Nippewalla group and all the Whitehorse group into the Gaudalupian Series. Newell (1940) had tentatively correlated the Whitehorse sandstone of Oklahoma and Panhandle Texas with the Capitan limestone on the basis of fossils. Maher, on the contrary (1954; 1958), tentatively correlated the Day Creek dolostone with the Forelle limestone of Wyoming, which is a tongue of the middle part of the Phosphoria complex in Wyoming and can hardly be younger than the middle of the Guadalupian Series.

On the chart the Nippewalla and Whitehorse groups are arranged in accordance with the current usage of both the Oklahoma and Kansas Geological Surveys (Personal communications from C. C. Branson and R. C. Moore). The Quartermaster formation and its equivalents are here placed opposite the Rustler and Dewey Lake formations on the advice of R. C. Moore (Personal communication), but C. C. Branson would place them just above the Rush Springs sandstone.

80. Correlation of the Dunkard group of Ohio, West Virginia, and Pennsylvania with the early Permian is based on fossil plants and needs critical modern restudy. These deposits have been described in great detail by Cross *et al.* (1950) and summarized by Cross and Schemel (1956) who conclude that the evidence for Permian age is not very conclusive and that the lower part, at least, may prove to be of Pennsylvanian age.

H. L. Berryhill writes (Personal communication)

"In November, 1959, representatives of the U. S. Geological Survey met with representatives of the West Virginia, Pennsylvania, and Ohio surveys to consider the age and lower boundary problems of the Dunkard group. The four organizations agreed to henceforth designate the age of the Washington formation as Pennsylvanian-Permian and

that of the Greene as Early Permian. These units will be so designated on the forthcoming revised geologic map of Pennsylvania, and in future publications of the U. S. Geological Survey.... There are neither lithologic nor faunal-floral bases for differentiating the Washington and Greene formations anywhere in the Dunkard Basin. The subdivision of Stevenson (1876) has been handed down mainly through tradition. His Washington "group" is actually nothing but a facies. Away from the northern edge of the basin, the Washington "group" has few of the lithologic characteristics of the "type" area. During recent detailed mapping of Belmont County, Ohio, by the U.S.G.S., no bases for subdivision of these rocks were found. In that area these rocks were classified as Dunkard group, Washington-Greene formations undifferentiated."

81. The whole of Prince Edward Island is underlain by nonmarine deposits, largely redbeds, which contain fossil plants and vertebrate fossils. The sequence is thick but has not received modern study. The plants are clearly Paleozoic rather than Triassic. According to A. S. Romer (Personal communication) "the one recognizable fossil then is a skull of a good sphenacodont pelycosaur, which is close to or maybe even identical with *Dimetrodon* of the Texas redbeds and quite certainly indicates an age equivalent to either Wichita or Clear Fork."

82. It is possible that the Kazanian Stage extends somewhat higher than here indicated.

85 and 86. Arranged according to McWhae *et al.*, 1958.

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Short Notes

BULLETIN OF THE GEOLOGICAL SOCIETY OF AMERICA
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NEW OCCURRENCES OF TRIASSIC SEDIMENTARY ROCKS IN CHEDABUCTO BAY AREA, NOVA SCOTIA

By I. M. Stevenson

Abstract

Several outliers of sedimentary rocks of Triassic age have recently been discovered in the Chedabucto Bay area of Nova Scotia. The paleogeographic distribution of Triassic rocks in Nova Scotia extends at least 85 miles farther east than previously recognized.

In June 1957, while engaged in geological mapping of Chedabucto Bay map area for the Geological Survey of Canada, the writer examined several outcrops of sedimentary rock that appear identical to rocks of Triassic age found along the shores of Minas Basin some 85 miles to the west. Although fossil evidence was lacking at that time, the sediments were assumed to be Triassic (Stevenson, 1959) and mapped as the Annapolis formation (Weeks, 1948), mainly on lithological grounds. Fossils have recently been found which definitely confirm the Triassic age of the rocks (D. Baird, 1959, personal communication).

The Triassic rocks outcrop at three localities along the shores of Chedabucto Bay (Fig. 1). The two largest outcrops, near Bigby Head and McCaul Island, form wave-cut cliffs. The third outcrop is in the bed of a small stream flowing south into Ragged Pond.

The rocks comprise brownish-red conglomerates, sandstones, and siltstones gradational into each other. Well-rounded pebbles of white vein quartz, a distinctive criterion of the coarser clastic members, are present in the conglomerate. The coarser members are quite friable and readily crumble under the hammer. The siltstones are of the same brownish-red hue, spotted with greenish areas of reduction.

Bedding is well developed in the sandstones and siltstones, but poorly defined in the more massive conglomerates. Torrential-type cross-bedding is ubiquitous in the sandstone members.

The strata are cut by several faults with varied strikes and unknown displacements. Dips are steep in the Bigby Head and McCaul Island exposures, but the beds at Ragged Pond are relatively undisturbed.

Although these Triassic outliers are of small areal extent, they are of considerable geological interest. Previously, no record of Triassic sedimentation was known beyond the eastern tip of Minas Basin. It now appears that deposition occurred for a distance of at least 85 miles northeast of this point, thereby indicating a greater distribution of Annapolis-type sediments than heretofore realized.

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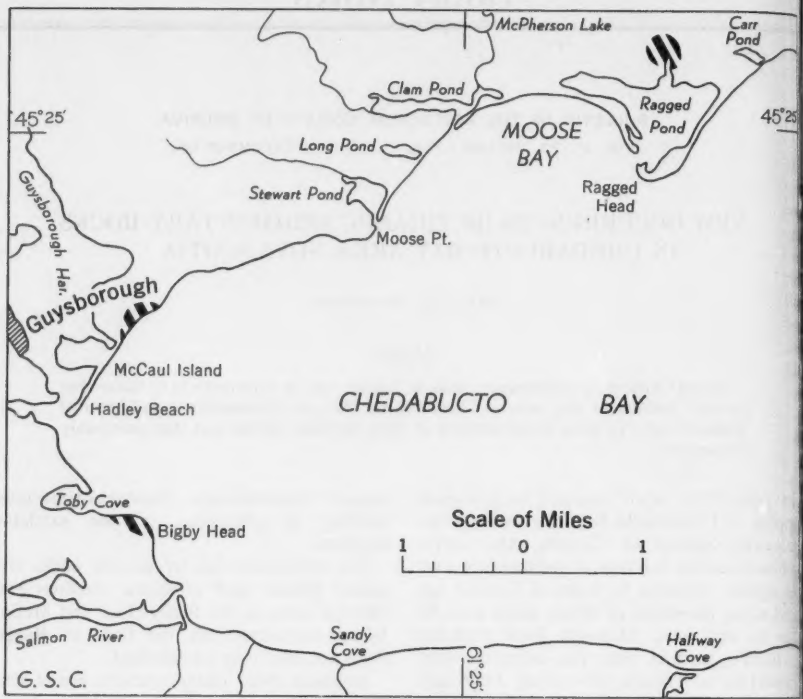

FIGURE 1.—SKETCH MAP OF CHEDABUCTO BAY REGION, NOVA SCOTIA
Showing location of the Triassic outcrops

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DIAMICTITE, A SUBSTITUTE TERM FOR SYMMICTITE

BY R. F. FLINT, J. E. SANDERS, AND JOHN RODGERS

In the April 1960 issue of this BULLETIN, we proposed the term *symmictite*, for terrigenous sedimentary rocks that contain a wide range of particle sizes, and the companion term *symmicton*, for nonlithified equivalents (Flint, Sanders, and Rodgers, 1960). Since publication, we have learned that *symmictite* is preoccupied because of its use (Sederholm, 1924, p. 148) for a homogenized eruptive breccia, in which the mixing implied by the term refers to different kinds of rocks (country rock plus intrusive rock) rather than to different grain sizes in sediments. Although the word *symmictite* as defined by Sederholm is little known outside the literature describing the Precambrian rocks of the Fennoscandian shield, it was used in Sederholm's sense by the late Dr. Simo Kaitaro (1953, p. 31, 66). A related term, *symmict structure*, was still earlier employed (Sauramo, 1923, p. 82) to refer to laminae, in varved sediments, in which particle sizes are mixed heterogeneously rather than arranged in a graded relationship. That usage coincides in essence with ours.

Rather than contribute to the confusion that would result if the term symmictite were applied differently in two branches of geology, we propose to substitute *diamictite* (Gr. *dia-mignymi*, to mingle thoroughly) for symmictite as previously defined by us. In parallel manner we propose to substitute *diamicton* for symmicton as defined before.

Acknowledgment

We express our thanks again to our colleague, C. B. Welles, for his suggestion of the terms proposed.

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